ÉNERGIE ET RADIOSCIENCES

Performances of rectennas subject to uncertain EM environment

Sébastien Lalléchère * and Blaise Ravelo**

**Université Clermont Auvergne, Université Blaise Pascal, Institut Pascal, 4 Avenue Blaise Pascal, F-63178 Aubière, sebastien.lallechere@univ-bpclermont.fr*
***IRSEEM EA 4353, Graduate School of Engineering ESIGELEC, Avenue Galilée, F-76801 Saint Etienne du Rouvray*

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Abstract

This paper deals with the modeling of uncertainties inherent to rectennas' design. Those systems are known to ensure power conversion of ambient electromagnetic (EM) fields (and power P_{RF}) into DC electrical power (P_{DC}) at a given frequency or for adapted frequency bandwidth. By essence, they are subject to uncertain EM conditions, both including environment (EM sources) and constitutive electronical parameters. After a brief description of the problem under consideration, the random modelling of the electrical behavior of rectenna is proposed. Finally, we demonstrate on numerical test cases the importance of taking into account random variations of inputs to properly qualify the performances of rectennas.

1. Introduction and motivations

Rectennas are used to convert the electromagnetic (EM) power represented by P_{RF} which is generally represented by RF signal radiating at certain frequency into DC power P_{DC}. The input power corresponds to the electrical signal provided by the antenna represented by the current source $J_{RF}(\omega)$ in parallel with its internal admittance $Y_a(\omega)$. Fig. 1 summarizes the basic architecture of the rectenna and is inspired by [1]. The performance of this system can be expressed by its DC-voltage pattern and ripple amplitude [2] which can be respectively formulated through the relations (1) and (2):

$$\eta_{VDC}(\omega) = \frac{V_{DC}(\omega)}{V_{RF}(\omega)}, \quad (1)$$

$$r(\omega) = max\left|\hat{V}_{DC}(t)\right|_{t \in Tf}, \quad (2)$$

where ω is the frequency of interest, η_{VDC} represents the efficiency ratio (voltage), and $r(\omega)$ stands for the ripple of collected signal. It is defined regarding final time of simulation T_f (last 20 ns) and maximum oscillating levels $\hat{V}_{DC}(t)$ normalized to V_{RF}.

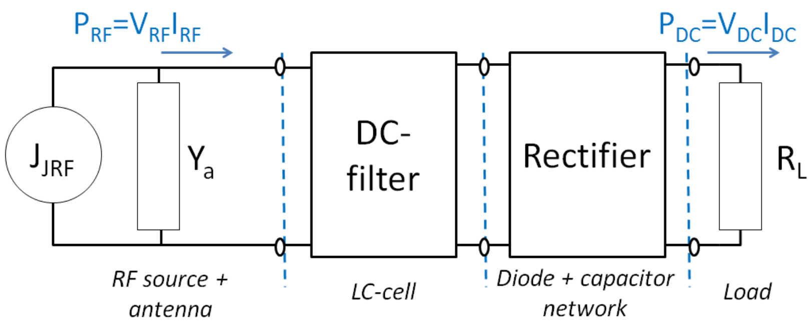


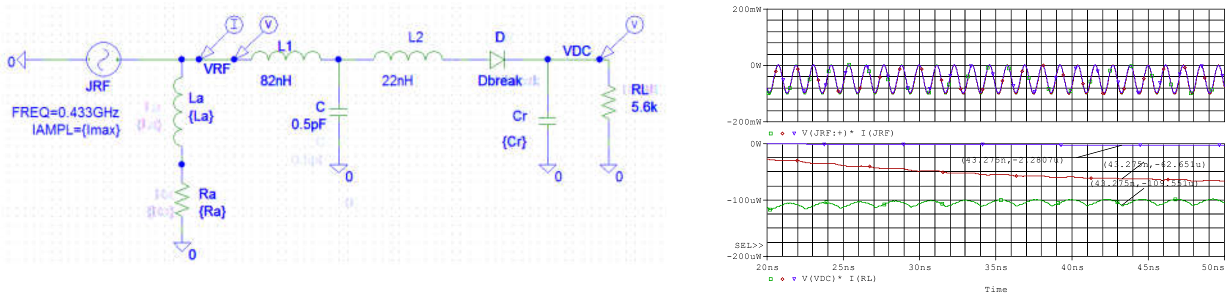
Fig. 1. « Generic » rectenna architecture from [1].

Similar to all electronic circuit, the efficiency of rectenna is influenced by the parameters of its constituting three blocks (Fig. 1). The rectenna is essentially constituted by the reception antenna, DC-pass filter and a rectifier. The antenna is assumed as modelled by a current source in parallel with RL-input impedance. A DC-filter is designed with a LC cell. The final stage is the rectifier with diode and capacitor. Due to their harsh conditions of using and manufacturing, rectenna systems are subject to many sources of uncertainties (random coupling with EM environment, manufacturing, electronic design). For instance, random variations regarding components [6] embedded in capacitor network may imply unwanted spoiling of the performances (e.g., efficiency and ripple in relations (1) and (2)). Realizations and manufacturing tolerances also in some cases [7] lead to drifts (especially regarding simulations and measurements). For the overview on the assessment of this performance, a statistical analysis is proposed in the next section.

2. Parametric SPICE overview of rectenna's behavior

The rectenna circuit was designed in SPICE environment. Based on the transient parametric simulations, the influence of the rectenna parameters will be examined in the next paragraph.

2.1. Deterministic rectenna design and first parametric overview



(a) (b)

Fig. 2. (a) SPICE schematic of the equivalent circuit for rectenna simulation [1]. (b) Transient responses of the rectenna circuit shown in Fig. 2a: C_r={10pF (green line), 100pF (red line), 1nF (blue line)}, at f = 433 MHz, and from simulation time 20 ns to50 ns.

Fig. 2a depicts the SPICE schematic of the equivalent circuit of proposed rectenna [1]. It can be seen that the antenna is replaced by the current source with amplitude I_{max} = 100 mA and operating frequency f = {433MHz, 868MHz}. The internal impedance of rectenna is composed by RL-series network R_a = 10 Ω and L_a = 1 nH. The DC-filter is constituted by the L1-C-L2 cell. The final stage is constituted by the diode *D* and the capacitor C_r between 10 pF and 1 nF (for instance, see Fig. 2a). The transient responses of the rectenna (e.g., by considering the harmonic current source I_{max} and f_0 = 433 MHz are displayed in Fig. 2b. It shows how the variable C_r values may lead to huge variation regarding transient responses of P_{RF} (-P_{RF}, top in Fig. 2b) and P_{DC} (-P_{DC}, bottom in Fig. 2b). As expected, the design of rectennas requires harsh tradeoff between power stability (bottom, green line, *Cr*=10 pF) and weak levels of energy collected (bottom, blue line, *Cr*=1nF). Results given by *Cr*=100 pF [1] are still oscillating but brings higher power levels (bottom, red line in Fig. 2b). Although those results are well-known, the problem becomes increasingly complex when assuming random inputs (e.g., modelling *Cr* as a random parameter varying over a given range). Obviously, several techniques are available: the next section will give a quick overview of potential methods.

2.2. Theoretical foundations and statistical methodology

Monte Carlo (MC) simulations [4] figure as reference methods since their non-intrusiveness is well-appreciated (e.g., SPICE proposes some dedicated MC modules); unfortunately they require a huge number of random simulations. Indeed, MC techniques are also well-known for their slow convergence rate which is often a drastic drawback. That is the reason why we propose alternative technique to statistically assess the effect of several rectenna components (e.g., DC-filter and rectifier cells) on EM energy conversion (i.e., throughout the parameters given in relations (1) and (2)). We will put the focus on the assessment of mean contributions and on the sensitivity of parameters using stochastic collocation method (SCM). It was successfully used in the framework of electromagnetic compatibility [5] and antennas [6], and its principle (given in details in [5]) is similar to advanced sampling process. In comparison to MC simulations, SCM was characterized by better efficiency (for instance decreasing the computing costs), but still with high accuracy of results as demonstrated in antennas [6] and EMC [5] contexts.

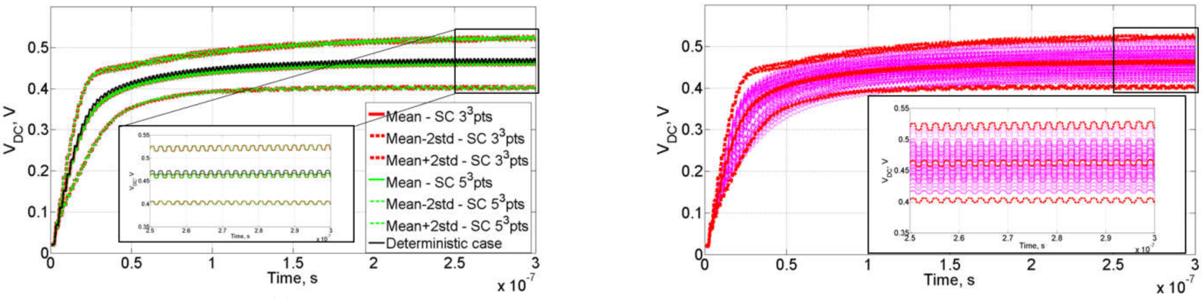
Next section will be dedicated to the presentation of numerical results regarding several configurations of deterministic modelling of rectenna (Figures 1 and 2a). Three different test cases are considered in this work; First, the test cases #1 and #2 are considered assuming random variations for DC-filter parameters with uniform distributions depending on their initial values (here L1 = 82 nH, C = 0.5 pF, and L2 = 22 nH, Fig. 2a) and the level of uncertainty around mean (respectively 10% and 5% for cases #1 and #2). Then, a final random configuration (test case #3) will be considered by assuming capacitor *Cr* (rectifier) as uniformly distributed (with a level of uncertainty of 5%). In this final test case, an optimization process will be provided to compute the optimum values (*Cr*) and improve the design of rectennas under uncertain condition (see section 3.2).

3. Advanced design of rectenna with uncertain assumptions

As previously announced, this section is dedicated to the numerical and statistical results obtained from the three test cases: first, assuming random variations around DC-filter components (#1 and #2); then evaluating the effect of random capacitor *Cr* at rectifier stage (#3).

3.1. Assuming uncertain components for DC-filter

This part is dedicated to the modelling of "uncertain" DC-filter (Fig. 1) components (here assuming components L1, C and L2 are uniformly distributed around their initial values, see Fig. 2a).



(a) (b)

Fig. 3. Test case #1 at frequency f = 433 MHz assuming 10% uncertainty around L1/C/L2. (a) Convergence of SCM in function of SC orders 2 (SC 3^3pts, red) and 4 (SC 5^3pts, green); Mean and standard deviation (std) comparatively to deterministic case (i.e. without uncertain assumption). (b) MC mean and standard deviation from SCM (red) in comparison to MC mean trends from 500 (pink) simulations.

Fig. 3 gives an overview of the convergence of SCM considering V_{DC} statistics and including three random parameters (test case #1, Fig. 3a): slight differences exist between deterministic data (black curve, given by strictly initiating L1, C and L2 with mean values (i.e. respectively 82nH / 0,5pF / 22nH) and mean trends from SC (given with 27 and 125 Spice simulations, respectively red and green curves). SCM allows quantifying dispersion of results (without any extra computing costs, see details in [5-6]) throughout +/- 2 standard deviation calibers. The spread of statistical results are compared in Fig. 3b with 500 MC simulations (pink curves) validating the benefit that can be taken from SCM: decreasing about 3 times the time and computing efforts needed in comparison with 500 MC simulations; moreover trustworthy statistical results are obtained (convergence), enabling to improve the assessment of rectenna's performances from relations (1) and (2).

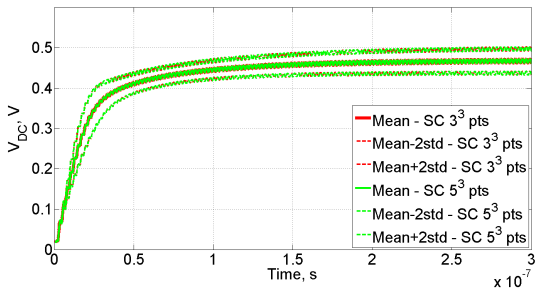


Fig. 4. Test case #2 at frequency f = 433 MHz, assuming 5% uncertainty around L1/C/L2. Convergence of SCM in function of SC orders 2 (SC3^3pts, red) and 4 (SC5^3pts, green); Mean and standard deviation (std) given by SCM are in accordance.

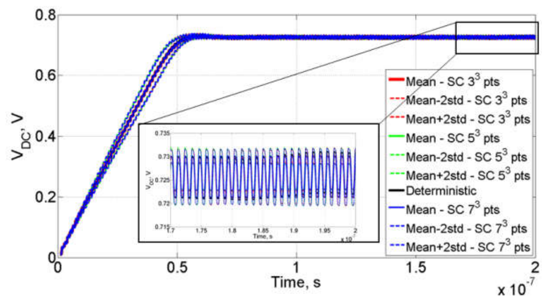


Fig. 5. Test case #2 at frequency f = 868 MHz, assuming 5% uncertainty around L1/C/L2. Convergence of SCM in function of SC orders 2 (SC3^3pts, red) and 4 (SC5^3pts, green); Mean and standard deviation (std) comparatively to deterministic case (i.e. without uncertain assumption).

Figures 4 and 5 respectively show the behavior of V_{DC} statistics (mean and standard deviation) relatively to simulation time (test case #2) at frequency *f1* = 433 MHz (Fig. 4) and *f2*=868 MHz (Fig. 5). It should be noticed that mean trends of DC-voltage are higher at *f2* than at *f1*; moreover the statistical dispersion around mean of V_{DC} is lower at *f2*. The convergence of SCM is still very interesting (relatively to MC) since 125 simulations are sufficient to precisely assess V_{DC}-levels. Fig. 5 proposes for information mean and standard deviation of V_{DC} obtained with 343 simulations (SCM order 6, blue curves).

As expected, Fig. 4 demonstrates how minimizing uncertainty levels of random parameters L1/C/L2 (i.e. 5% in Fig. 4 and 10% in Fig. 3) may decrease the dispersion of V_{DC}-statistics around mean trend (almost keeping same levels: around 0.466 V in Fig. 1a, and 0.462 V in Fig. 4). The use of SCM brings quantified information about the influence of random variations of DC-filter design (via the quality of electronic components). Finally, regarding criterion given in relations (1) and (2), and similarly to previous comments, the mean performances of rectenna are slightly influenced by random variations: converged results from test case #2 (Fig. 4) show that η_{VDC} is comprised between 44,7% (SCM) and 45,1% (deterministic case), while ripple r is around 0,9% (0,91% and 0,93% respectively for SCM and deterministic case). The real benefit from SCM is provided throughout computing (without any additional cost) standard deviation and higher-order statistical moments to better design rectennas. Its efficiency in comparison with MC is also a key interest as it will be discussed in next section.

3.2. Optimization of variable capacitor *Cr* with uncertain assumptions

According to [1], the proposed rectenna may be efficiently designed with *Cr* = 100pF. The aim of this part is to demonstrate the interest of stochastic techniques to improve the optimization of the design of rectennas with uncertain parameter *Cr*. The work from [3] clearly recalls that the uncertainty surrounding discrete components (e.g. *Cr* capacitor) is comprised between 5% and 10% of their nominal value. In the following we will consider test case #3, *f1* = 433 MHz and *f2* = 868 MHz, and will compare SCM (order 10 to ensure both accuracy and convergence) with results from 500 MC simulations. Relying on first parametric results (Fig. 2b), the range of variations for *Cr* is [10 pF; 1 nF]. The optimization issue will be bounded regarding last assumption and considering *Cr* as a random parameter given by: $C_r = C_r^0(1+\epsilon u)$, where ϵ stands for the level of uncertainty (here 5%), u is a random variable uniformly distributed between -1 and +1, and C_r^0 is the current mean value considered during optimization process which is based on so-called golden section search and parabolic interpolation as depicted in [8]. EMC work [5] clearly demonstrated that applying an optimization procedure with uncertain condition make the problem far more complex to handle. We will validate SCM accuracy and efficiency relatively to MC approach in the context of several optimization issues.

Tab. 1. Results of optimization (minimum/maximum, number of calls, and optimum Cr values) regarding test case #3 (assuming uniform distribution of random parameter Cr, 5% of uncertainty level; # of calls are not given for deterministic tests). Statistical results are focused on mean (<.>) values considering ripple (r) and η_{VDC}/r ratio.

	Test case #3, *f1* = 433 MHz				**Test case #3, *f2* = 868 MHz**			
	Ripple (r)		*Target function (TF)*		*Ripple (r)*		*Target function (TF)*	
	min<*r*>	#calls/*Cr*	max<*TF*>	#calls/*Cr*	min<*r*>	#calls/*Cr*	max<*TF*>	#calls/*Cr*
Deterministic case	0,184%	- / 773 pF	200,3	- / 700 pF	0,171%	- / 438 pF	392,0	- / 527 pF
SCM (11 points)	0,189%	341 / 760 pF	196,0	319 / 758 pF	0,171%	330 / 464 pF	363,7	341 / 463 pF
MC (500 simul.)	0,192%	14500 / 762 pF	193,8	15000 / 751 pF	0,173%	14500 / 480 pF	361,8	15500 / 476 pF

Results in Tab. 1 gives an overview of the statistical computations achieved respectively without uncertain assumptions (i.e. deterministic case, information about number of calls during optimization process being irrelevant), with SCM and with MC. In order to take into account the effect of uncertainties both considering η_{VDC} and ripple, we define a Target Function TF as follows: *TF* = η_{VDC}/r. Tab. 1 shows the accuracy of SCM comparatively to 500 MC simulations since results agree well regarding test case #3 at *f1* = 433 MHz and *f2* = 868 MHz. Taking into account uncertainties slightly modified the performances of rectenna (increase for min<*r*> and max<*TF*>, where <.> stands for mean). It is to be noticed that optimum values of capacitances *Cr* agree well between SCM and MC (at maximum less than 4% differences), but with far more calls during optimization process based upon mean computations (at least more than 40 times speedup with SCM). However, the optimal rectennas' design is different from deterministic to stochastic (i.e. SCM and MC) cases (at maximum more than 12% differences between deterministic and stochastic optimization procedures); that lays emphasis on the importance of efficient statistical tools in this framework.

4. Conclusion

This paper has demonstrated the benefit that has to be expected from the design of rectennas under uncertain assumptions. In this proposal, the influence of random variations regarding the electronic components from DC-filter block was statistically evaluated with several stochastic methods. It was shown that SCM may offer an interesting alternative to MC simulations in this framework. Moreover, by assuming random variations of rectenna's parameters (here variable capacitor *Cr*) during an optimization procedure, SCM has demonstrated its robustness and efficiency to correctly predict statistics of different target functions depending on the performances of rectennas (e.g. η_{VDC} and ripple). This provides a helpful tool to efficiently lead statistical investigation during the design steps of rectennas.

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