ÉNERGIE ET RADIOSCIENCES

Optimal energy harvesting from a stack of serially-connected rectennas

Khaled F*, Kharrat I**, Vuong T-P**, Allard B***

** Université de Lyon, INSA de Lyon, Ampère, UMR CNRS 5005, France, firas.khaled@insa-lyon.fr*
*** Université Grenoble Alpes, IMEP-LAHC, Grenoble, France*
**** Université de Lyon, INSA de Lyon, Ampère, UMR CNRS 5005, France*

Keywords: Rectenna, efficiency, stack, voltage balancing circuit (Fr: rendement, rectenna, association, circuit d'équilibrage de tension).

Introduction

Recently, interest in wireless applications has led to an ever-increasing use of batteries. Many efforts focus the possibility to extend the battery life by reducing the consumption of the devices. Other solutions collect ambient energy for energizing these devices [1]. Energy harvesting consists of the process of capturing and converting a part of the ambient energy into useful electrical energy. Ambient energy is available in the environment in different forms; light, thermal, mechanical or chemical. Recently, wireless energy-harvesting technology has received special attention due to the omnipresence of electromagnetic fields related to wireless sources and the growth in use of wireless devices in many applications like mobile phones and sensor networks [2]. Due to the development of new radio technologies, the radio sources are becoming heavily populated: television, radio, cellular, GSM, GPS, WiFi, satellite and radar. Radio Frequency (RF) signals can be collected and converted into electricity by rectennas, which consists of an antenna and a rectifier circuit, to provide a sustainable power supply from radio environment [3,4,5]. Only a small amount of the energy transmitted from the wireless sources can be scavenged and converted into electrical energy. Consequently, RF energy harvesting suffers from low output power and low output voltage that can limit their applications [6]. Energy densities can vary from 0.01 $\mu W/cm^2$ to 300 $\mu W/cm^2$ depending on the location the RF power source and the rectenna geometry. It is still sufficient to supply wireless nodes [7]. Most commonly used wireless sensor nodes consume hundreds of µW in active mode and few µWs in sleep mode [8]. RF systems, like the other energy harvesting systems, are considered technologies that can supply low power applications and remove the need for batteries for low power devices, hence overcoming economic, energetic and environmental issues. [9].
Various energy harvesting circuit topologies have recently been developed. They are generally based on the non-linear characteristics of diodes that allow the AC to DC energy conversion. These topologies depend on different criteria including diode position and antenna design: single series structure [10], shunted mounted diode structure [11] or voltage doubler structure [12] that allows reaching higher DC voltage. Several kinds of antennas have been used in harvesting energy circuits such as patch antenna [13], dipole antenna [14], multilayer antenna [15] and antenna array.
The energy produced by an array of rectennas can be stacked in several configurations to increase the output power for supplying the desired application [16,17]. In one approach, a single rectifier can be matched with multiple antennas [18]. In another approach, each antenna in the stack can incorporate its own rectifier [19] and the DC voltage outputs are combined in parallel, series, or in a hybrid manner [20].
A serial association may be suitable to increase the output voltage of the stack to an acceptable level for the application. However the variable and unpredictable levels of available power lead to dispersion in the characteristics of rectennas that can affect the global efficiency of the serial association [21]. The main objective of this paper is to optimize the efficiency of a serial stack of rectennas.

1. RF energy harvesting circuit components

The key element of a wireless energy transfer system is the rectenna. It consists in collecting energy from one or more sources through receiving antennas. The recovered power is converted to DC power through a rectifier consisting of one or more Schottky diodes, or diode-mounted MOSFETs, in order to supply electronic devices. Zero-bias Schottky diodes are selected thanks to their low threshold voltage, high switching speed and ability to operate at high frequencies. Circuits based on MOSFETs are acceptable but fitting back the threshold voltage of a MOSFET increases the complexity of the rectifier. Fig. 1 depicts the schematic of a rectenna. Because of its non-linear behaviour, the diode generates high harmonic signals on either side of the circuit that modify the performances of the rectenna especially in multiple frequency environments. For this reason, two filters (RF and DC) are designed on each side of the rectifier

circuit. The RF-side band-pass filter aims to avoid energy losses by eliminating radiation harmonics of higher order modes that are reflected back to the antenna. The DC-side low-pass filter allows delivering DC current to the load but blocks all RF components including the fundamental component at 2.45 GHz. The latter central frequency is selected as an example here. In that way, the remaining RF energy is reflected to the diode to enhance the mixing and consequently the RF to DC conversion of the input signal. An impedance matching network is added between the RF filter and the diode to ensure maximum power transfer.
A lab-scale rectifier is composed here of two SMS7630 diodes. Two diodes have been used to maximize the output voltage of the circuit. The diodes are connected in opposite way for a full-wave rectifying effect. Two stubs are used as low-pass DC-filter. The access line presents a low impedance in order to match the rectifier to 50 Ω (w = 3.88 mm). The line is fabricated on 800 µm-thick Rogers 4003 substrate. The rectifier is 35 mm long and 20 mm wide as shown in Fig. 1-b.

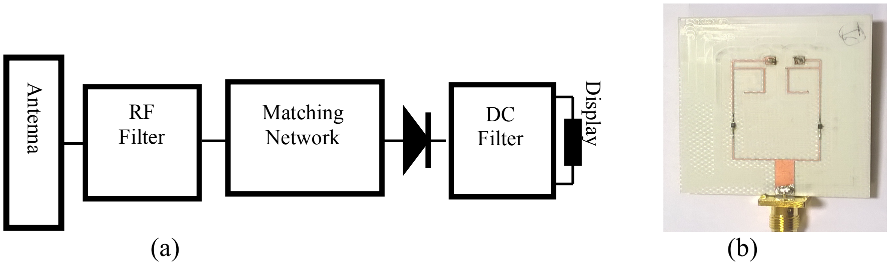

Figure 1. Conceptual view of RF energy harvesting system (a), photography of the studied rectifier (b)

2. Energy harvesting from a stack of rectenna

In series-connected rectenna, the individual voltages add-up at the output while a common current flows through the stack as shown in Fig. 2. The serial association is considered to step-up the voltage while increasing the output power to an acceptable level for real applications (>1 V).

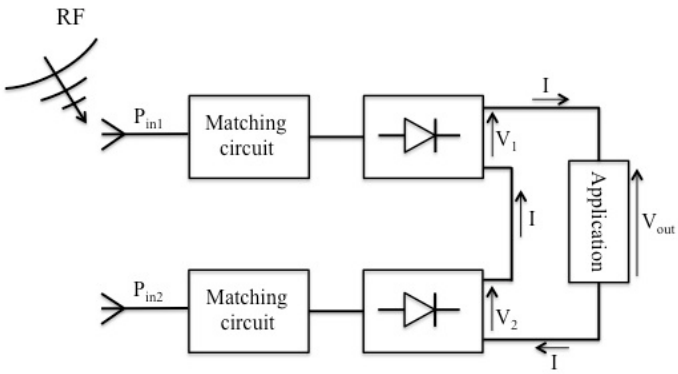

Figure 2. Serial association of rectennas

The rectenna behaviour is the focus here. Two rectennas are supplied by a single electromagnetic power source with different values of input RF power (-0.5 dBm and 0 dBm respectively) to simulate the case of variable levels of available ambient energy.
Each rectenna was characterized by changing the load as function of current to obtain the output voltage and consequently determine the output power. Fig. 3 shows the electrical characteristics of 2 rectennas. Rectenna 1 has an open circuit voltage of 0.8 V and 43 µW of maximum output power while Rectenna 2 has an open circuit voltage of 1.12 V and 250 µW of maximum output power. The maximum power point for each rectenna is different due to different levels of available electromagnetic energy or different efficiency values.

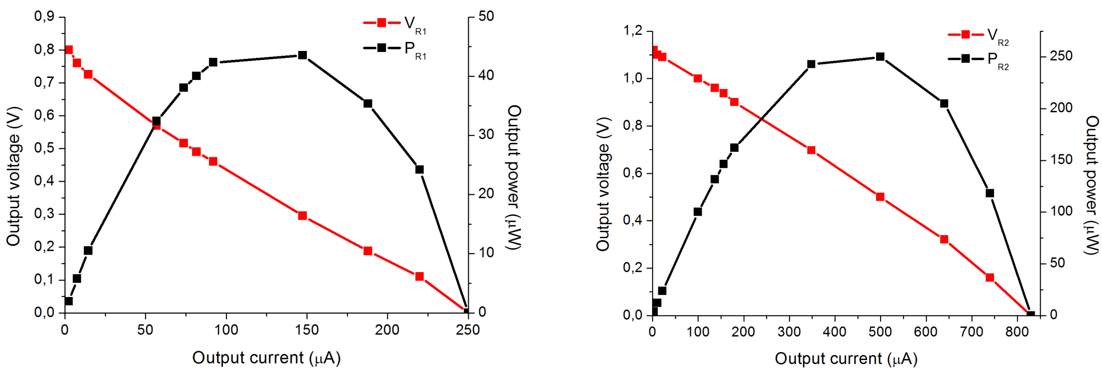

Figure 3. Electrical characteristics of two rectennas

When the two rectennas are serially connected, the rectennas in the stack are not able to operate at their maximum power point what leads to a low stack efficiency. The maximum efficiency of the serial stack is 38.5% where the first rectenna operates at 72% and the second at 30% of their maximum available power respectively. Fig. 4 shows the electrical characteristics of the serial rectennas. For an output current higher than 240 μA, the voltage of the first rectenna is reversed. Voltage reversal phenomenon is detrimental to power generation because the concerned rectenna (the weakest) will absorb some electrical energy from the other rectenna.

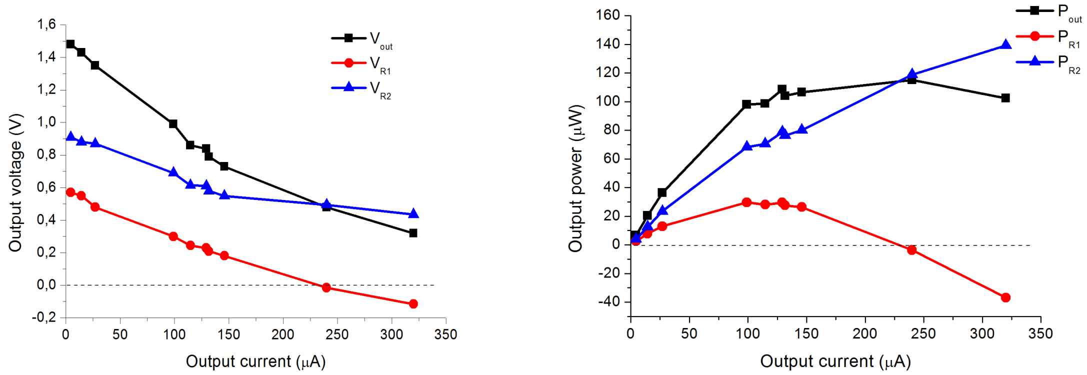

Figure 4. Output voltage of the serial stack and the voltage of each rectenna in the stack

3. Voltage balancing circuit for energy harvesting

Many voltage-balancing circuits have been studied in literature for batteries and supercapacitors to enhance the efficiency and extend their lifetime [22, 23, 24, 25]. Application of voltage balancing circuits to Microbial Fuel cells (MFCs) has been studied to solve the problem of serial association of non-uniform MFCs [26]. In a serial association, connecting a parallel capacitor with the generators in the stack, can transfer some energy from the strongest generator(s) to the weakest one(s) to achieve the balancing as shown in Fig. 5. This method is known in literature as switched-capacitor method. The maximum exegetic efficiency reaches 92% of the maximum power point for a serial stack of 2 MFCs [26, 27]. Considering that rectennas have similar electrical characteristics as MFCs, application of this circuit to a serial stack of rectennas may optimize the efficiency of the stack. The switched capacitor circuit (SC) only requires switches (SW), capacitors (C) and a single oscillator [28]. The switched-capacitor circuit therefore offers good perspectives for rectennas.

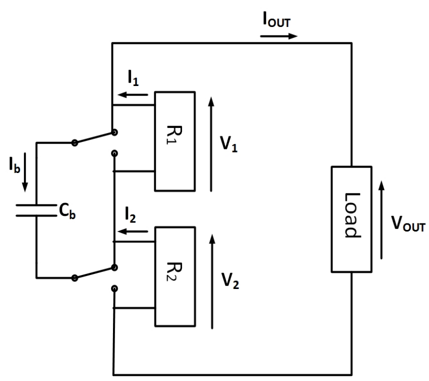

Figure 5. Schematic of the switched capacitor circuit

The circuit is fabricated by using SPDT switches with low internal resistances (0.5Ω) as shown in Fig.6. The value of the balancing capacitor and the switching frequency were sized experimentally. For a frequency of 1 kHz, the balancing is not efficient and the system has an exegetic efficiency of 39.5% (of the maximum available power point). Increasing the frequency will enhance the performance of the circuit. A high frequency (about 1 MHz) increases the losses in the circuit and decreases the total efficiency. It was found that with a capacitor of 500 nF and a switching frequency of 10 kHz, the circuit has the best efficiency. The serial association of rectennas in Fig. 4 offers a maximum exegetic efficiency of 61.4% with voltage balancing circuit. Fig. 7 shows the electrical characteristics of the serial stack with the balancing circuit. The output power is increased from 113 μW (without voltage balancing circuit) to 180 μW with the application of voltage balancing circuit. At high current densities, no voltage inversion phenomenon was noted.

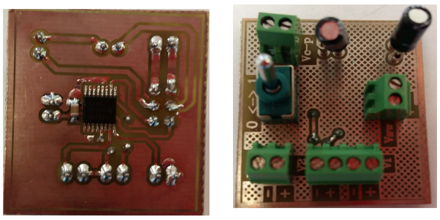

Figure 6. PCB of the balancing circuit

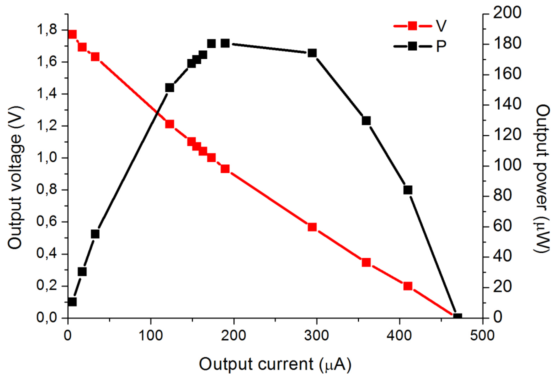

Figure 7. Electrical characteristics of the balanced stack

4. Conclusion

In this paper, energy harvesting from a serial stack of rectennas is studied. The dispersion of rectenna performances is one issue that will decrease the efficiency of a serial association compared to individual performance of rectenna. A circuit that enables voltage balancing across serially associated rectennas is required. Balancing voltage across all rectennas in the stack achieves a higher output voltage and therefore better performances. We have experimentally demonstrated the interest of a voltage balancing circuit to optimize the performance of the association of rectennas and prevent the voltage inversion in the weakest rectenna(s). The switched-capacitor circuit is an efficient voltage balancing circuit for low power generators like rectennas. This voltage-balancing circuit offers a low-cost effective solution to increase the energy generation of rectennas to supply low power application. The SC circuit can be extended to a stack of a large number of rectennas. The integration of the circuit will decrease losses and the volume of the circuit and enhance the performances.

Références bibliographiques

1- S.P. Beeby, M.J. Tudor, and N.M. White, “Energy Harvesting Vibration Sources for Microsystems Applications”, Measurements Science and Technology, Vol. 17, pp. 175- 195, 2006
2- F.E. Little, J.O. McSpadden, K. Chang, and N. Kaya, “Toward Space Solar Power: Wireless Energy Transmission Experiments Past, Present and Future”, Space technology and applications international forum, AIP Conference Proceedings, Vol. 420, pp. 1225- 1233, 1998.
3- G. Monti, L. Tarricone, and M. Spartano, “X-band planar rectenna,”IEEE Antennas Wireless Propag. Lett., vol. 10, pp. 1116–1119, 2011.
4- W. C. Brown, “The history of power transmission by radio waves,” IEEE Trans. Microw. Theory Tech., vol. MTT-32, no. 9, pp. 1230–1242, Sep. 1984.
5- B.H. Strassner and K. Chang,“ Microwave power transmission,”in Encyclopedia of RF and Microwave Engineering. Hoboken, NJ: Wiley, 2005, vol. 4, pp. 2906–2919.
6- Dolgovet et. al. (2010). “Power management system for online low power RF energy harvesting optimization”, Cir. and Sys. I, IEEE Trans. on, 57(7), 1802-1811.
7- Drayson technologies Ltd., “RF Energy Harvesting for the Low Energy Internet of Things,” 2015.
8- Hambeck Christian et al. “A 2.4 µW wake-up receiver for wireless sensor nodes with -71 dBm sensitivity”, IEEE International Symp. Circuits and Systems 2011; 534–537.
9- Vullers et al. (2009). Micropower energy harvesting. Solid-State Electronics, 53(7), 684-693.
10- Sun, H., Guo, Y.X., He, M., Zhong, Z. “A dual-band rectenna using broadband Yagi antenna array for ambient RF power harvesting”, IEEE Antenna and Wireless Propagation Letters, 2013, 12, pp. 918-921.
11- Yamashita, T., Honda, K., Ogawa, K. “High efficiency MW-Band rectenna using a coaxial dielectric resonator and distributed capacitors”, Proc. EMTS, 2013, pp. 823-826.

12- Alam, S. B., Ullah, M-S., Moury, S. "Design of a low power 2.45 GHz RF energy harvesting circuit for rectenna", Proc. ICIEV, 2013, pp. 1-4.
13- Tudose, D.S., Voinescu, A. " Rectifier antenna design for wireless sensor networks", Proc. CSCS, 2013, pp. 184-188.
14- Visser, H.J. "Printed folded dipole antenna design for rectenna and RFID application", Proc. EUCAP, 2013, pp. 2852-2855.
15- Yang, X.X., Jiang, C., Elsherbeni, A.Z., Yang, F., Wang, Y.Q. "A novel compact printed rectenna for data communication systems" IEEE Trans. Antennas and Propagation. 2013, 61, (5), pp. 2532-2539.
16- Olgun, U., Chen, C. C., and Volakis, J. L. (2011), "Investigation of rectenna array configurations for enhanced RF power harvesting" Antennas and Wireless Propagation Letters, IEEE, 10, 262-265.
17- T.East,"Aself-steering array for the SHARP microwave-powered air- craft," IEEE Trans. Antennas Propag., vol. 40, no. 12, pp. 1565–1567, Dec. 1992.
18- J.Zbitou, M.Latrach, and S. Toutain,"Hybrid rectenna and monolithic integrated zero-bias microwave rectifier," IEEE Trans. Microw. Theory Tech., vol. 54, no. 1, pp. 147–152, Jan. 2006.
19- J.Hagerty,F. Helmbrecht, W.McCalpin, R.Zane, and Z.Popovic,"Re- cycling ambient microwave energy with broad-band rectenna arrays," IEEE Trans. Microw. Theory Tech., vol. 52, no. 3, pp. 1014–1024, Mar. 2004.
20- N. Shinohara and H. Matsumoto, "Dependence of dc output of a rectenna array on the method of interconnection of its array elements," Elect. Eng. Jpn., vol. 125, no. 1, pp. 9–17, 1998.
21- N Degrenne, V Marian, C Vollaire, F Buret, J Verdier and B Allard "Voltage Reversal in Unbalanced Rectenna Association", Antennas and Wireless Propagation Letters, IEEE, 2012
22- B. Y. G. Altemose, " Batteries and Fuel Cells Achieving cell balancing for lithium-ion batteries", Electronic Products, pp. 21-22, 2008
23- Baronti, and G. Fantechi, in IEEE Vehicle Power and Propulsion Conference, 2011
24- Diab, Y., Venet, P., & Rojat, G. (2006) "Comparison of the different circuits used for balancing the voltage of supercapacitors: Studying performance and lifetime of supercapacitors", In Proceeding of the 2nd European Symposium on Super Capacitors & Applications.
25- S. Vighetti, Y. Lembeye, J. P. Ferrieux, and J. Barbaroux, "Photovoltaic module and shadow: Study and integration of a current balancing system ", in Proceedings of EUPVSEC (2010)
26- Khaled et al. (2015). Voltage balancing circuits strategies for a stack of serially-connected microbial fuel cells for energy harvesting", Eur. Phys. J. Appl. Phys. 71,1, 10904.
27- Khaled, F., Ondel, O., & Allard, B. (2015) "Optimal Energy Harvesting From Serially Connected Microbial Fuel Cells", Industrial Electronics, IEEE Transactions on, 62(6), 3508-3515.
28- Daowd, M., Antoine, M., Omar, N., Van Den Bossche, P., & Van Mierlo, J. (2013) "Single switched capacitor battery balancing system enhancements", Energies, 6(4), 2149-2174.