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Ultra-low Power RF Energy Harvesting for Wirelessly Powering Portable Microsystems

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Abstract—This paper presents some research results from the Ampere/SATIE Laboratories concerning RF energy harvesting sources and relative power management circuits.

Keywords—RF energy harvesting, rectenna, ultra-low power, low Voltage, DC-DC converter

I. INTRODUCTION

Wireless energy transfer born in 1862 when Maxwell establishes its theory of electromagnetism. In fact, Maxwell predicts that energy could travel without the need of a specific material medium. Next, Hertz and Marconi have realized experiments that prove that wireless energy transfer is possible. Wireless energy transfer is possible through mainly three ways: inductive magnetic coupling, resonant magnetic coupling and radiated RF energy.

In the case of inductive and resonant magnetic coupling the energy is transferred between two proximate coils [1-2]. The transfer is realizable within the near-field area which limits and reduces considerably the possible transmission distance (some cm to some tens of cm). The transmission effectiveness is very good. This technic finds a lot of consumer applications such as wireless recharge systems for electrical toothbrushes wireless mouses and electric cars.

For radiated transfer the energy is not transferred using coils but using antennas which operate with ultra-high frequency ($>1\text{GHz}$) and far-field allowing to obtain large possible transfer distances (up to some km). This technic was firstly used for high power energy transfer, but unfortunately for reasons of poor effectiveness it was abandoned and used only for information transfer. In fact, in far-field energy transfer the RF power is scattered and the captured quantity is in most case very small as regard to the emitted one.

However, RF energy transfers found very interesting applications in low-power system such as wireless sensors. RF energy allows, in fact, to provide wireless power source for autonomous low-power systems.

II. LOW-POWER RECTENNAS

The association of a receiving antenna and an RF-DC rectifier circuit is called a rectenna (rectifying antenna). Rectenna operation principle is illustrated in Fig. 1. The

incident RF power is captured by an antenna under the form of a high frequency sine wave. This is then transformed into DC power by the diode-based converter. A HF filter ensures impedance matching between the antenna and the diode rectifier around a central frequency (2.45GHz) for optimal power transfer. The output DC filter smooths the output DC voltage and current by attenuating high frequency harmonics present in the RF signal or generated by the rectification process itself.

In the case of low incident power levels (below 1mW), the rectifier is often based on a series-mounted diode. This structure offers the best compromise between DC output voltage level and conversion efficiency at low incident power levels [3]. Furthermore, zero-bias Schottky diodes are often used in this case due to their low threshold voltage (around 150 mV) and their low junction capacitance (0.18 pF) [4].

A prototype of a single series-mounted diode rectenna was fabricated on a low-cost 1.6 mm FR4 substrate. In order to evaluate the rectenna output characteristic, the fabricated prototype was tested under wide range of input RF power and output load resistance. RF power is directly supplied by a power source through a SMA cable. Current-Voltage (I-V) and Efficiency-Load (η -R) characteristics are shown in Fig. 2.

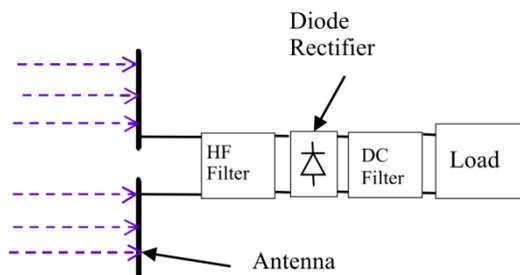


Figure 1. Block diagram of a rectenna circuit

I-V characteristic are almost parallel straight lines. In addition, the conversion efficiency is maximal for a specific fixed output load value. Therefore, the rectenna output DC model is a voltage source in series with its internal impedance. This internal impedance is equal to the optimal load value (2.4k Ω in this case). For a -15dBm (30 μ W) level of injected RF power, the output open-circuit voltage is equal to 300mV. In this case, the maximum output DC power is around 10 μ W.

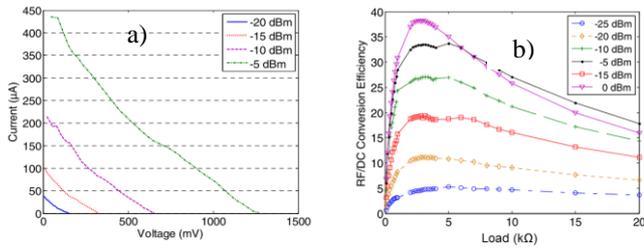


Figure 2. Series-mounted rectenna output characteristic: a) Current-Voltage, b) Efficiency-Load

In order to be able to use this energy, a specific DC-DC converter topology is needed in order to provide a conventional voltage level (over 1V).

III. POWER MANAGEMENT SYSTEM FOR RECTENNAS

As shown previously, low power rectennas deliver low voltage levels (<1V). In order to be able to power conventional circuit as wireless sensors, a special step-up structure would be needed. Furthermore, a completely autonomous structure offers more application opportunities and more flexibility. An autonomous architecture avoids the use of any external start-up assistance (battery, precharged capacitor or mechanical switch). In this case of autonomous operation, a start-up circuit is used. The start-up circuit is a special low-power and low-voltage DC-DC converter.

In our case, the start-up circuit is a resonant Armstrong-oscillator-based converter. This topology [5-6] is based on the use of a normally-on JFET and a high step-up transformer. It will guarantee autonomous operation under ultra-low power (from some μW) and low voltage (from some hundreds of mV) conditions. Due to its relatively poor performances (no regulation and poor efficiency in general), such a circuit is only used during transient phases. Experimental measurements based on fabricated prototypes show good performances. In fact, the minimum start-up voltage is around 100mV (200mV for the source open-circuit voltage) and the minimum power around $3\mu\text{W}$. thanks to its high step-up ratio, the converter provides an over 1V voltage level. Those results are unexampled as regard to the state of the art of autonomous low voltage and low power DC-DC converters as it is demonstrated in ongoing published papers and in [5-6].

An under-voltage lock-out circuit (UVLO) can be used in order to allow the start-up capacitor to be charged to a sufficient voltage level before the control circuit will be operational.

Once the start-up capacitor is charged through the start-up converter, the principal converter is activated. This converter is an inductive Flyback converter operating in Discontinuous-Conduction-Mode (DCM) in order to achieve static impedance matching with the rectenna. This is an indirect or static Maximum-Power-Point-Tracking (MPPT) technic. As the rectenna internal impedance is almost constant over a wide range of RF power, this technic allows to obtain very excellent matching results with ultra-low quiescent power overhead (< $2\mu\text{W}$). Experimental measurements demonstrate more than

99% of effectiveness for the impedance matching (ratio of the harvested power by the maximum available power). The efficiency of the converter is 50% at $10\mu\text{W}$, more than 75% for $100\mu\text{W}$ and achieves a peak of 78% for $400\mu\text{W}$ of input power. This efficiency includes the converter internal losses and also the control circuitry losses.

Once the Flyback output reaches a convenient voltage level, the start-up circuit is disabled and during the steady-state phase, the principal converter control circuit is only powered by the output. Nonetheless, in some cases, the available power is not sufficient; the start-up circuit is used alone. The system topology is depicted in Fig. 3.

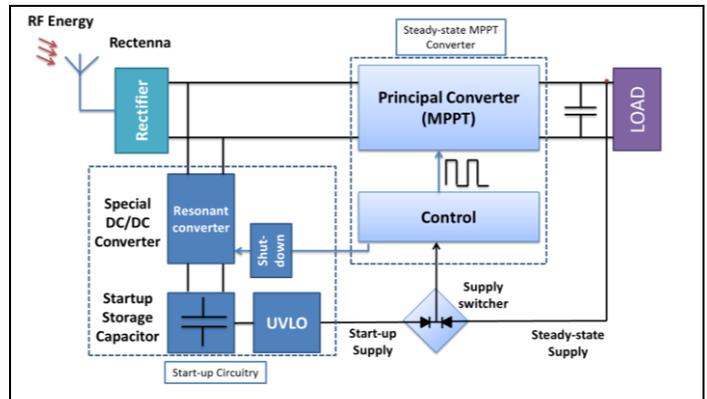


Figure 3. Power management system for Rectennas

IV. CONCLUSION

The developed power management system allows to optimally interfacing low power rectennas. In additions, the system don't need additional external energy source allowing then to power autonomously, solely and wirelessly low power electronics form RF energy.

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