

Optimized Power Management Circuit for Implantable Rectenna for In-Body Medical Devices

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Abstract— For many years, RF wireless harvesting systems have been investigated, but only a few of RF sources have been able to generate sufficient energy that can be used as feasible source for implantable medical devices like implantable rectenna, it could provide unlimited energy for the lifespan of implanted devices. In order to harvest the maximum power from implanted rectenna, power management system is needed. However, most of power management systems are not efficient due to power consumption in control circuitry. This paper presents a fabricated rectenna with 63% power efficiency and an optimized power management circuit to improve the efficiency of DC-DC converter, where the rectenna is used as power source, this is accomplished by using particle swarm optimization technique. This design improves the efficiency of optimized power management circuit by 10% comparing with conventional power management circuits over a wide range of input power, allowing harvesting more power from rectenna and delivering it to medical device; it can extend the battery life of implantable medical devices.

Keywords— Implantable Medical Devices (IMD's), Energy Harvesting, Rectenna, RF Energy, Power Management Circuit, Resistor emulation, PSO, and Low Power Applications.

I. INTRODUCTION

The need for ultra low power for standalone embedded systems that need to operate for very long time devices is growing rapidly. Requirements in this market for low power, long life, push limits of current technologies of RF energy sources and existing solutions that maybe applicable to low power applications. Therefore, new techniques and creative designs are required to meet urgent requirements of today's cutting edge low power devices.

RF energy harvesting systems are increasingly required to satisfy needs of wireless systems [1], but the most important goal is improving environmental compatibility and adaptability without detriment to their performance. Power sources for biomedical applications using RF wireless harvesting systems have gained a considerable attention recently [2-8], such as inductive coupling [7], capacitor coupling [7], magnetodynamic coupling [8], far-field radio frequency methods such as rectenna. These methods can be used for longer distances applications. An implantable rectenna is the key for designing implantable medical devices (IMD's), Rectenna currently has gained considerable attention to be used as power source for

implantable medical devices. This is because rectenna is easy in integration with microwave integration circuits, low cost, and small volume. Recently, most of the research on design of implantable rentennas has focused on issues related to compact size, biocompatibility, power efficiency, life span of implantable medical devices.

In this paper, an antenna is designed as a power receiving device and combined with high frequency rectifiers. Also, the paper presents an approach for gathering near maximum power by improving the efficiency of DC-DC converter from RF energy sources. Convenient power management circuits are not suitable for very low power RF energy sources due to the high-power consumption of components that used in the system. Based on that, particle swarm optimization (PSO) technique is successfully applied to select proper values of inductor and on-time to minimize power consumption, improve DC-DC converter efficiency, and the efficiency of maximum power point tracking (MPPT) system where the converter efficiency is used as fitness function and inductor and on-time are chosen as optimized parameters [9-13].

The paper is organized as follows: Section II describes the RF energy source system and generated power. The power management circuit is presented in Sections III. Simulation results are discussed in Section IV. Finally, Section V concludes the paper.

II. RF ENERGY SOURCES (RECTENNA)

Great innovations of the last century have ushered continuous progress in many areas of technology, especially in the form of miniaturization of RF energy sources. This progress shows a trend towards consistent increases in power density; and towards a decrease in power requirements due to miniaturization and consumption power [14]. A lot of RF energy sources can be used in order to provide power to low power applications [15]. Most of them have potential characteristics and can be designed to deliver a maximum power like Rectenna. It is an antenna with rectifier device can be used for converting electromagnetic energy into electrical energy.

As shown in Fig. 1, Most of rectenna designs consist of three basic parts: an antenna, matching network to maximize the power delivered to the load, and a rectifier circuit. The main

component of rectification process is schottky diode which is less power consumption, faster switch, and less voltage drop than regular diodes. The selection of schottky diode depends on forward voltage, power requirements, I - V characteristics as described in expression (1) as shown below, and maximum reverse breakdown voltage, current voltage characteristics is defined as [16]. In this work, the voltage doubler using two high frequency schottky diodes.

$$I_D = I_S \left[e^{\frac{V}{NKT}} - 1 \right] \quad (1)$$

where I_D is diode current, I_S is reverse saturation current, V is forward bias voltage, K is Boltzmann constant, T is absolute temperature, and N is ideality factor.

Since the rectenna is used for biomedical devices, operating frequency was chosen to be 2.4 GHz and the material used in antenna design could be biocompatibility material such as Silicon Carbide (SiC) or coated with biocompatibility material. In this work, the antenna was designed using Roger RO4350B material and it will be coated in the future, it is easy to integrate and fabricate and has low loss feature and this could maintain the power efficiency. Matching network is the next step in the design to achieve maximum power delivered and minimum return loss (S_{11}), it was designed based on the load impedance, source impedance, and the specifications of schottky diodes and then optimized using built-in optimization tool in Advanced Design System (ADS), DC block capacitor and smoothing capacitor were added to the design.

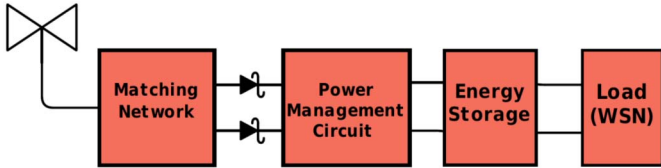


Fig. 1. Block diagram of RF energy harvesting system.

Many studies have been performed on amount of generated power from Rectenna such as [10], [11], [17], and [18] which showed the generated power range from (10 μ W) to (1W) but this power range varies with distance, path loss, antenna gain, and frequency. The efficiency of rectenna is measured by RF - DC ratio as shown below.

$$\eta_{RF-DC} = \frac{P_1}{P_{RF}} \quad (2)$$

$$P_{RF} = P_{\text{density}} * Ae \quad (3)$$

$$Ae = \frac{\lambda^2 G}{4\pi} \quad (4)$$

where P_{density} is power density, P_1 is output power of rectenna, Ae is effective area for patch antenna for example, λ is

wavelength, and G is antenna gain. Note that the effective area of patch antenna is larger than the physical area because of fringing field effect and typically it is trimmed by 2-4% to achieve resonance at the desired frequency [19]. In order to calculate the effective area of patch antenna, expressions (5-7) are used to calculate the actual (L_p) and effective (L_{eff}) length of the patch antenna [20].

$$L_p = L_{eff} - 2\Delta L \quad (5)$$

$$L_{eff} = \frac{c}{2f\sqrt{\epsilon_e}} \quad (6)$$

$$\Delta L = 0.412h_p * \frac{\left\{ (\epsilon_e + 0.300) * \left(\frac{w}{h_p} + 0.264 \right) \right\}}{\left\{ (\epsilon_e - 0.258) * \left(\frac{w}{h_p} + 0.813 \right) \right\}} \quad (7)$$

where ΔL is the extended patch length, c is the speed of light, f is the operating frequency, ϵ_e is the effective dielectric constant, h_p is the height of the patch, and w is the width of the patch.

Fig. 2 shows a fabricated RF Rectenna at 2.4 GHz on Roger RO4350B [21] printed circuit board using milling machine. The matching network is realized with microstrip lines to ensure maximum efficiency. Signal generator connecting to 2.4 GHz monopole antenna was used as a power source in order to harvest energy by RF Rectenna in Center for Wireless and Microwave Information Systems lab at University of South Florida (WAMI Lab).

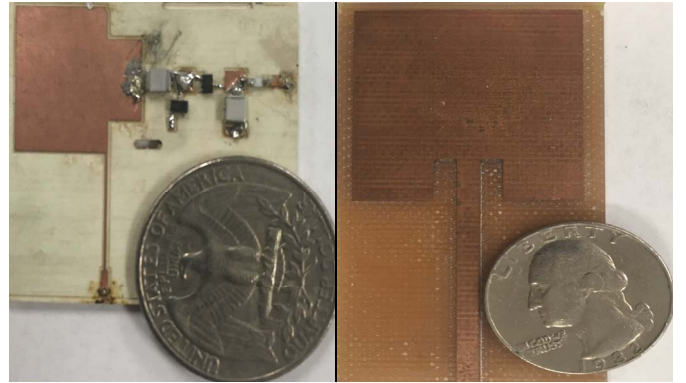


Fig. 2. Fabricated Rectenna with matching network and rectifier stage.

The generated power curves in Fig. 3 show that the rectenna maximum generated power (maximum efficiency point) over a range of input power levels can be reached with optimum load impedance. For the rectenna of Fig. 2, this resistance is 400 Ω . Based on that, the rectenna was designed and fabricated.

Fig. 4 shows the power measurements obtained experimentally from rectenna comparing with simulation results over a range of power received by antenna with different load impedances. It is observed that the efficiency is about 63% (75% simulation). Good agreement between results obtained from simulation and the measurement is observed. The differences between the measurement results and the simulation ones could be due to the discontinuity effects, the connectors, the fabrication process, losses, and measurement errors.

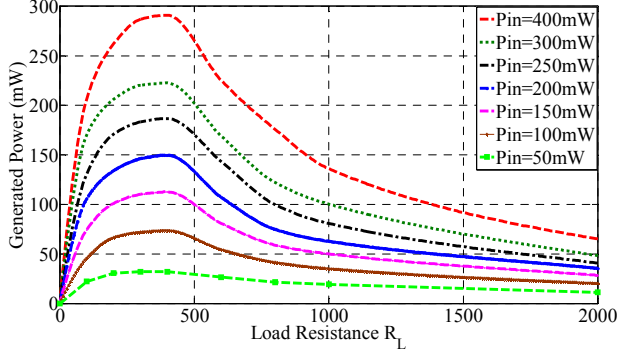


Fig. 3. Simulation results of power generated by Rectenna over a range of input power for different loads.

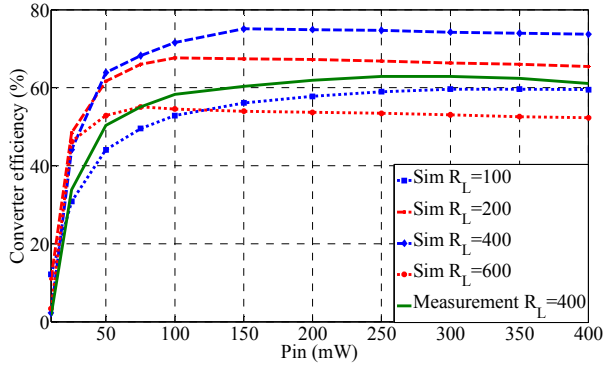


Fig. 4. Measurement and simulation results for the efficiency of Rectenna.

III. POWER MANAGEMENT CIRCUIT

To improve the efficiency of RF energy harvesting system, an optimized power management circuit is proposed using resistor emulation and particle swarm optimization technique.

A. Resistor Emulation

In the last decade, resistor emulation technique has been used to track the maximum power point for low power applications, most commonly in photovoltaic and wind applications. The idea is based on using DC-DC converters as a resistor emulator to be a matching network between the load and rectenna. Therefore, power management system can harvest maximum power and deliver it to load, where resistance depends on values of inductor and on time. If boost converter is operated in DCM as shown in Fig. 5 below, then resistance emulation is [10], [11], [23]

$$R_{op} = R_{em} = \frac{2LT_{control}}{t_{on}^2 \alpha} \left(\frac{M-1}{M} \right) \quad (8)$$

where L is inductance, t_{on} is on time of MOSFET, α is switching factor, and $M = V_o/V_{in}$.

At very low power incoming from RF source, input voltage of the converter is typically very low and therefore expression (8) can be simplified to [10]:

$$R_{op} = R_{em} = \frac{2LT_{control}}{t_{on}^2 \alpha} \quad (9)$$

where $\left[\frac{M-1}{M} \right] \approx 1$. For simplicity, $T_{control}$ assumed to be half of on time, and then resistance emulation is [10]

$$R_{op} = R_{em} = \frac{4L}{t_{on} \alpha} \quad (10)$$

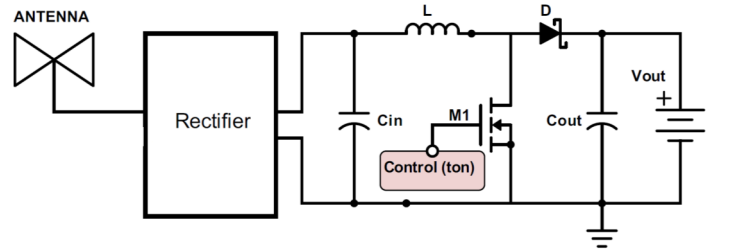


Fig. 5. Boost converter with control trigger for MOSFET.

B. Power Management Circuit Configuration with PSO

Particle Swarm Optimization (PSO) finds the best possible solution according to a predefined fitness function for a nonlinear problem by moving interacting particles and choosing best solutions by comparing the particle's best solution with the global best solution obtained by all particles [24]. This technique was proposed in 1995, based on analogy with biological swarming observed in insect swarms, bird flocks, and fish schools [25]. PSO technique is capable of achieving solid, accurate, and rapid solutions to several complex optimization problems. It is a stochastic, adaptive population-based optimization algorithm. It's a large number of searches using a group of particles, which is appropriate to solve large-scale optimization problems [26–28].

The aim of applying PSO algorithm is to have best values of L and t_{on} that can give maximum converter efficiency and harvest maximum power. The selection of values of inductor and on time for boost converter depends on power losses, emulated resistance, input power, and output voltage.

C. Selection of L and t_{on}

PSO optimization technique is used to find the best value of L and t_{on} that can output high converter efficiency by run simulation over expressions (11-17) where power loss includes

switching loss, conduction loss, and control loss as shown below.

$$P_{\text{loss}} = P_{\text{in}} - P_{\text{out}} = P_{\text{control}} + P_{\text{switching}} + P_{\text{conduction}} \quad (11)$$

$$P_{\text{conduction}} = (R_{L,\text{ESR}} * I_{L,\text{rms}}^2 + R_{\text{on}} * I_{L,\text{rms1}}^2 + P_{\text{Diode}}) * \alpha, \quad (12)$$

$$P_{\text{switching}} = \frac{\alpha}{2t_{\text{on}}} (V_o Q_{M1} + V_{\text{in}}^2 C_{\text{oss}_1}) \quad (13)$$

$$P_{\text{control}} = P_{\text{pwm}} * \alpha + P_{\text{operating}} \quad (14)$$

$$P_{\text{Diode}} = \frac{V_{\text{in}}^2}{V_o - V_{\text{in}}} \frac{V_D * t_{\text{on}}}{4L} \quad (15)$$

$$I_{L,\text{rms}} = \frac{1}{\sqrt{6}} \frac{V_{\text{in}} * t_{\text{on}}}{L}, \quad (16)$$

$$I_{L,\text{rms1}} = I_{L,\text{rms}} \sqrt{\frac{V_{\text{in}}}{V_o - V_{\text{in}}}}$$

$$R_{L,\text{ESR}} = (8e12 * L^4) + (1e10 * L^3) + (4e6 * L^2) + (3909 * L) \quad (17)$$

where $R_{L,\text{ESR}}$ is equivalent series resistance of inductor, R_{on} is MOSFET resistance when it's on, Q_{M1} is gate charge, C_{oss_1} is output capacitance of MOSFET, P_{pwm} is power loss of pulse width modulation, $P_{\text{operating}}$ includes other losses of control circuitry.

IV. SIMULATION RESULTS

To demonstrate the optimized power management circuit, the solution space is intended to keep parameters values that used in the optimization within acceptable ranges. Ranges used in this paper are listed in Table I.

Fig. 6 shows the simulation results of applying PSO on expressions (11-17) where the values of optimized L and t_{on} are taken after 1000 iterations or until the stop criteria is satisfied. It can be seen that the converter efficiency changes over the range of emulated resistances where the maximum converter efficiency of 91% is achieved and 80% is achieved for lowest value of input power generated from rectenna. These results confirm that the proposed resistor emulation using PSO algorithm could deliver significant improvements over existing solutions.

Fig. 7 shows a comparison between PSO simulation results of the optimized MPPT and simulation results of passive MPPT [10] for three different values of emulated resistances (200, 400 and 750Ω) over an extended power input range generated from rectenna (50μW-10mW), it is clear from Fig. 7 that converter efficiency results using PSO optimization is higher than the converter efficiency simulation results from [10] by 10% over an extended power input range and reaches up to 91% for $R_{\text{em}}=400\Omega$ and this value will be used later for designing full

system. Converter efficiency will vary once the whole system is fabricated since the system will be static for some specific optimized values. In future, micro controller will be added to improve the efficiency.

V. CONCLUSION

In this paper, a rectenna is designed to be used in implantable medical devices. Also, a methodology for optimizing maximum power point tracking system to improve the total efficiency of power management circuit of RF energy harvesting systems has been introduced. Results demonstrate that the maximum converter efficiency of rectenna design is 63% for optimum $R_L=400\Omega$. Also, the results show that proposed boost converter approach with PSO optimization is 91% for $R_{\text{em}}=400\Omega$ which is 10% higher than passive MPPT [3]. Another advantage is that the proposed approach can be applied for extremely low RF energy source and because the proposed work is valid for low emulated resistances. Therefore it can be applied with RF energy sources with low load resistance.

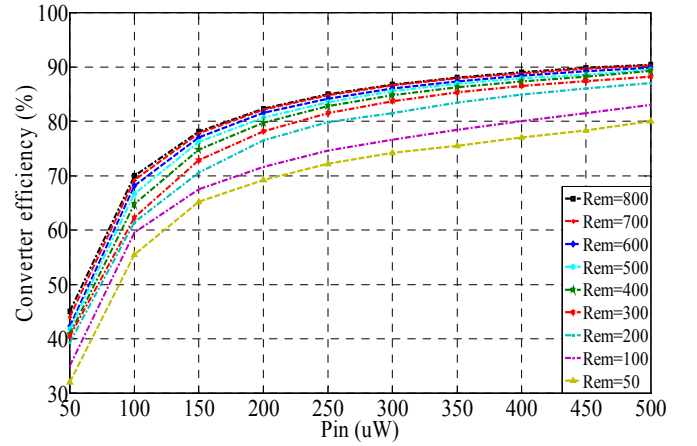


Fig. 6. Simulations at different values of R_{em} (50-800Ω) over P_{in} range (50 μW-500 μW).

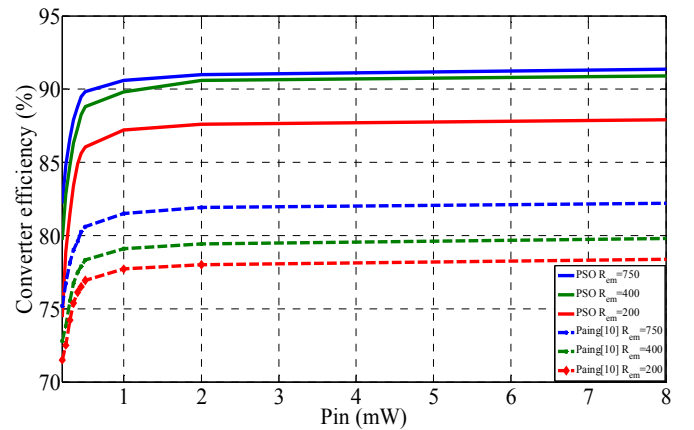


Fig. 7. PSO simulations results vs. simulations results of passive MPPT [3] of converter efficiency for R_{em} (200, 400, and 750Ω).

TABLE I. PSO PARAMETERS VALUES USED IN OPTIMIZATION

Parameter	Range
Emulated resistance	50-1500 Ohm
Input power	50-500 μ W
Output Voltage	4.15-4.20V
Inductance	10-500 μ H
On time	5-100 μ sec
Diode	V _d =230-270mV
MOSFET	R _{on} =0.344 Ω , M _g =650pf, C _{oss} =35pf

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