An Efficient RF Energy Harvester with Tuned Matching Circuit

Sachin Agrawal, Sunil Pandey, Jawar Singh, and P.N. Kondekar

PDPM-Indian Institute of Information Technology,
Design and Manufacturing Dumna, Khamaria P.O., Jabalpur, India-482005
{sachin.agrawal,sunilpandey,jawar,pnkondekar}@iiitdmj.ac.in

Abstract. Microstrip line with π matching circuits are very attractive because of high output power and good impedance matching which makes it an alternative over earlier matching circuit. This paper presents an RF energy harvester with microstrip line in series with tuned π-matching circuit that enables efficient power conversion at different RF input power under different load conditions. Matching circuit parameters were optimized for better efficiency. We have focused for specific input power range -15 to 10dBm for 3-stage, 5-stage and 7-stage of energy harvesting circuit. Optimum efficiency of approximately 80% is achieved at input power 0 to 10dBm for higher stages. Effect of load variation also shows that better efficiency is achieved for input power -10 to 10dBm for 3-stage, 5-stage and 7-stage of the harvesting circuit.

1 Introduction

In recent years use of wireless battery operated devices are increasing in broadcast and communication system. These devices continuously provide availability of free RF energy. The device like mobile phone, FM transmitter, AM and Wi-Fi operates at different frequency. The frequency spectra of these devices have different characteristics that depends on environmental conditions and surrounding locations for instance, humidity of the location. Energy harvesting circuits may be an atteractive solution to provide sufficient voltage for driving low power electronic circuits, which requires power in microwatts or milliwatts[1]. Energy harvesting is a process of extracting ambient energy available from the environment converting them into usable electrical energy.

Some related work has been done on solar energy harvesting since it has the highest energy density among other choices. However, it has a drawback of being able to operate only when sunlight is present. Wireless battery charging system as discussed in[2], shows the concept of charging a cellular phone battery, using monopole antenna that gives 50% efficiency for commercial product. Main motivation behind this work is the demand for self powered devices is increasing day by day and it become an attractive choice for remotely deployed low voltage battery wireless sensors.

This paper focuses on improving the efficiency of RF energy harvester that uses Wi-Fi and mobile signal because the maximum power intensity lies within

M.S. Gaur et al. (Eds.): VDAT 2013, CCIS 382, pp. 138–145, 2013.

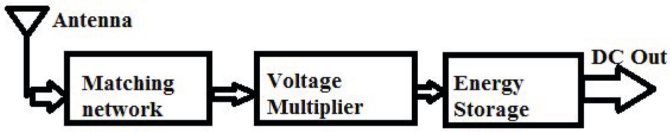

Fig. 1. Block Diagram of Energy harvesting circuit

the GSM bandwidth (890-915MHz and 935-960MHz), these signals carry maximum power but only a small amount can be harvested due to heat dissipation or absorption by other materials, so multiple stages of voltage multiplier are required to reach at appropriate level that can charge the wireless devices. Fig.1 shows the block diagram of a typical RF energy harvester circuit. The matching network composed of inductive and capacitive elements, ensures the maximum power delivery from antenna to voltage multiplier. The received RF power is converted into dc power by the voltage multiplier. The energy storage ensures smooth power delivery to the load, and as a reservoir for durations when external energy is unavailable[3].

Smaller number of the multiplier stages will make certain immediate charging of the capacitor, so the result is a small amount of the voltage generated that may be inadequate to operate sensor mote besides increasing the number of voltage multiplier stages, a slight change in the matching circuit parameter alters drastically the frequency range in which the efficiency of the energy conversion is maximum often by several MHz[3]. Hence, to design RF energy harvester involves a very essential part to choose the parameter of the circuit.

2 Design Methodology of Energy Harvesting Circuit

The incident RF energy need to be converted into usable dc power require an antenna with high directivity to receive more incident RF energy because the gain of the antenna is directly proportional to its directivity[11], a matching circuit to match the load impedance with the antenna impedance and rectifier circuit to develop the required voltage at the output, for this many approaches have been reported in the literature[4],[5],[6] and [7].

But according to Friis transmission equation[8]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{1}$$

where
P_r = Received power
P_t= Transmitted power
G_t= Gain of the transmitted antenna
G_r= Gain of the receiver antenna
R= Distance between the transmitter and receiver antennas
λ= wavelength of the transmitted signal.

The received signal strength diminishes with the square of the distance and frequency. The main challenge faced in harvesting RF energy is the free-space path loss of the transmitted signal with distance[3], it requires special sensitivity considerations in the circuit design. In this section We describe a new circuit that is capable of harvesting energy with high efficiency. Beginning with the selection of the circuit components, we choose the Dickson topology as shown in Fig.2, in this configuration parallel capacitors in each stage reduces the circuit impedance and hence, makes the matching task simpler[3]. In the following, we describe the design strategies for efficient RF energy harvesting circuit and its performance.

2.1 Selection of Matching Circuit

One of the crucial requirement of energy harvesting circuit is to transfer the total received power from antenna to the rectifier circuit. This can be done by proper selection of matching circuit and its components parameters, due to non-linear dependence of the rectifier impedance on the frequency and power, broadband impedance matching network is essential for maximum power transfer. If RF circuit is not matched we get reflected power, this reflected power builds standing waves on the transmission line between the source and load. Depending on the phase between the forward and reflected waves can either subtract or add. Because of that on the line we can get places where the voltage is the sum of both voltages or eventually places where the voltage equals zero (maximum current). If the standing wave is positioned in such a way on the transmission line so that the maximum voltage or current is applied to the circuit, they can be destroyed. There are various type of matching topologies are available such as resistive matching network that include only one resistor, here matching will be achieved but it is not a desirable solution because in resistive matching most of the power will be lost in the resistor. Another topology is transformer matching, it converts source power from one voltage and current level to another voltage and current level. Disadvantage of transformer matching is that it can match only the real part of the impedance, if there is a large amount of reactance in the load, a transformer will not eliminate these reactive components. Transformers however, works poorly at microwave frequencies. The L type matching network

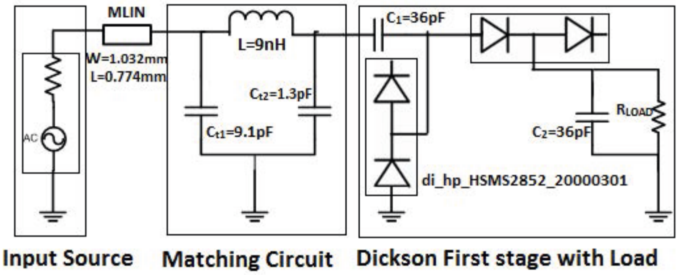

Fig. 2. Equivalent circuit of 1^{st} stage harvester circuit

consists of series capacitor with shunt inductor or series inductor with shunt capacitor. The bandwidth obtained by a single L-C network is not sufficient, however it can be increased by adding another section that forms π matching network. Advantage of the π networks is that by using an extra element there is an extra degree of freedom to control the value of quality factor in addition to perform impedance matching.

2.2 Selection of Diodes

As the peak voltage of the ac signal obtained from the antenna is generally much smaller than the diode forward voltage drop[9]. So here is requirement to select the diode with very low turn on voltage. Since RF energy harvesting is done in GSM range, therefore the diode with very fast switching speed is required, schottky diode have metal semiconductor junction in which metal side acts as the anode and n-type semiconductor acts as the cathode of the diode, which fulfills the requirement of very fast switching and low forward voltage drop. Because of its low forward voltage drop, less energy dissipation makes it most efficient choice for applications sensitive to efficiency. In this paper, we use schottky diode HSMS-2852 from Avago Technologies that has the turn on voltage 150 mV, as the edges of the schottky contact are fairly sharp, high electric field gradient occurs around them which limits the reverse breakdown voltage, low forward voltage and fast recovery time leads to increased efficiency. Moreover saturation current is another parameter that affects the efficiency of diode, so for obtaining high efficiency it is desirable to have diodes with high saturation current, low junction capacitance, and low equivalent series resistance (ESR)[3].

2.3 Selection of Voltage Multiplier Stages

The number of multiplier stages has a major influence on the output voltage of the energy harvesting circuit. Since only one or two stages are not sufficient to provide a fix amount of voltage that is capable to operate a wireless device, so we have to increase the number of stages. The efficiency, output voltage and output power are directly proportional to the number of stages, which is shown in Fig. 3, 4 and 5. For example from Fig.3 it can be seen that when the voltage multiplier stage is 1 the maximum efficiency is around 50%. As we going to increases the voltage multiplier stages from 1 to 7, it increases gradually. In Fig.4 V_1, V_3, V_5 and V_7 are the output voltages of 1-stage, 3-stage, 5-stage and 7-stage respectively with different values that shows the effect of number of stages. Fig.3 shows the another effect that, as we increases the order of stages the peak of efficiency is shifted toward the higher input power region.

2.4 Selection of Load Impedance

Every electronic device has a standard condition to operate for a specific range of load impedance, below and above this particular range the device performance

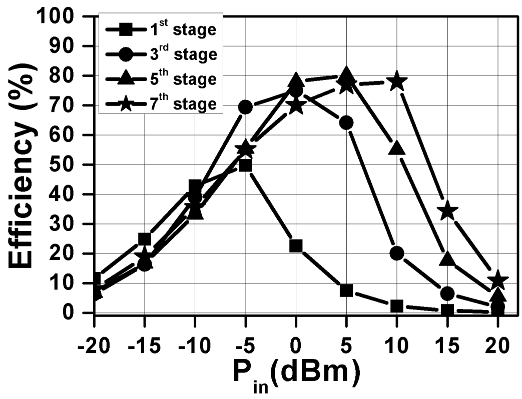

Fig. 3. Effect of number of stages on the efficiency of harvester circuit

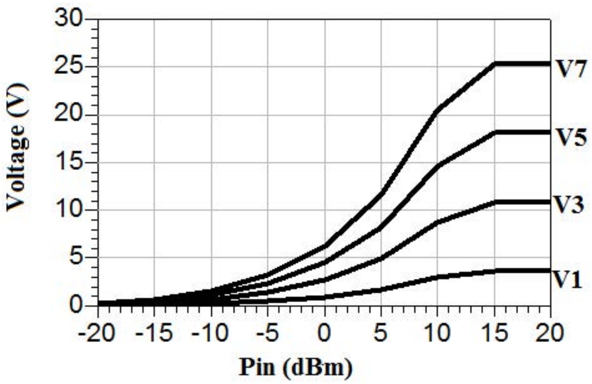

Fig. 4. Effect of number of stages on the output voltage of harvester circuit

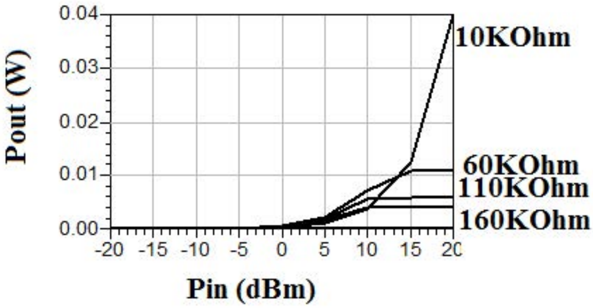

Fig. 5. Effect of load impedance variation on the output power of harvester circuit

is going to degrade. Energy harvesting circuits also have some specific range of load impedance that varied according to the number of stages, types of nonlinear device, and the choice of reactive component, therefore it is important to verify the selection of load impedance range and its impact on the circuit performance.

3 Simulation Results, Analysis and Discussion

Our aim is to calculate the steady state solution of nonlinear circuit or measurement of the various frequencies present in the system, so we use the harmonic balanced analysis (a frequency domain method). The another method so called transient analysis (time domain) is not used due to the reason that it must collect sufficient samples for the highest frequency component and it involves significant memory and processing requirement.

For simulation the values of inductor L, tuned capacitors C_{t1}, C_{t2} and stages capacitor are 31nH, 5.81pF, 0.66pF and 36pF repsectively. Width and length of microstrip transmission line is 1.032mm and 0.774mm respectively, here all simulations are performed at 915MHz.

We simulate the effect of load impedance on the output power and efficiency of the circuit with input power sweep -20 to 20dBm and load impedance sweep value 10-160kOhm for RF input power. Fig.5, 6, 7 and 8 shows the effects of load impedance. We examine that the circuit attains the highest efficiency at some particular load impedance. From Fig.6, 7 and 8 it is clear that the circuit gives highest efficiency in case of 60kOhm, it reduces drastically if the load value is too low or too high. In[10], for 0dBm input power at 950 MHz an efficient Periodic Steady State(PSS)-based power matching circuit gives 55.2% efficiency for RF to DC converter system. In[3], harvester circuit provides the highest efficiency 71%, the proposed circuit gives the maximum efficiency nearly equal to 80% for 3-stage, 5-stage and 7-stage which is shown in Fig.3. From Fig.6, 7 and 8 it is

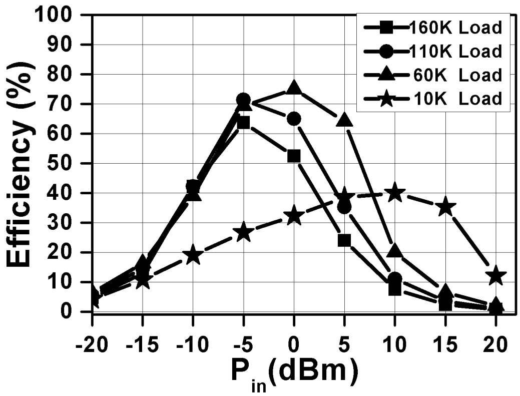

Fig. 6. Effect of load impedance on the efficiency of 3^{rd} stage of harvester circuit

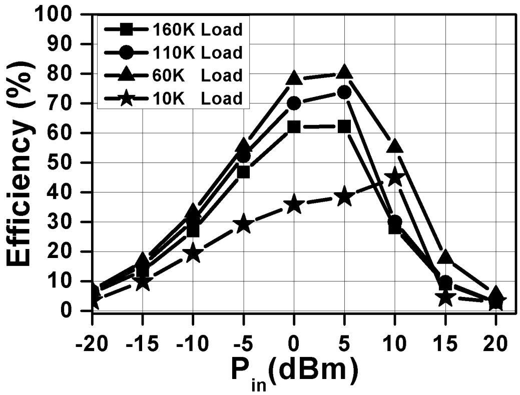

Fig. 7. Effect of load impedance on the efficiency of 5^{th} stage of harvester circuit

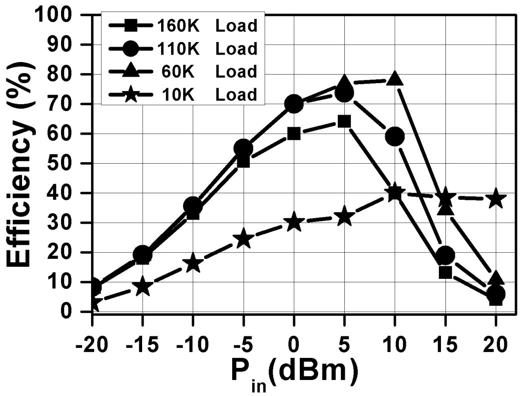

Fig. 8. Effect of load impedance on the efficiency of 7^{th} stage of harvester circuit

shown that efficiency is better for input power -10 to 10dBm over[3]. Optimum efficiency is for input power -5 to 5dBm for 3-stage and 5-stage as shown in Fig.6, 7 and for input power 0 to 10dBm for 7^{th} stage as in Fig.8. From Fig.4 it is clear that output voltage is nearly equal to[3], but the output power is increasing over[3] due to increased current arised at output terminal.

4 Conclusions

This paper introduces an RF energy harvester with tuned π-matching circuit for different stages and load variations. Simulation result of efficiency and power shows the improvement over existing harvester circuit. To obtain more improvement in output voltage and power, multiple antenna or array of antenna can be used but it will increase the size or cost of the circuit so for future work a feedback circuit can be proposed that will improve the power and efficiency.

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