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DESIGN OF SELF-COMPENSATED RECTIFIER WITH AUXILIARY CIRCUIT FOR RADIO FREQUENCY ENERGY-HARVESTING APPLICATIONS

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By

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May 2022

Chair : Assoc. Prof. Noor Ain Kamsani, PhD
Faculty : Engineering

Billion-plus devices will reportedly be connected to the internet via the "Internet of Things" (IoT). Most of these gadgets, including wireless sensors that are wirelessly connected to the internet, will not have a wired connection to the electrical grid and will instead rely on the energy stored in the batteries to operate themselves. Due to its lifespan and capacity constraints, the battery power source is a barrier to expanding a wireless sensor network to hundreds or millions of nodes. Energy harvesting is a practical method for powering at least specific wireless sensors and devices. Since RF energy harvesting is becoming more widely available, integrated, and compatible with wireless networks, it has become one of the most common energy scavenging technologies. Due to route loss, fast signal attenuation over distance, poor power efficiency of RF-DC converters, and restrictions restricting the highest allowable broadcast signal intensity, RF energy harvesting is severely constrained in its ability to capture large amounts of energy. Even if a matching network is utilized to minimize the input power losses received by the antenna and enhance the power transfer to the rectifier, transistors cannot function at the minimal power level required without an effective rectifier design. Enhancement of the efficiency of RF rectifiers and the reduction of the power consumption of the sensor circuitry and wireless transmitter necessary for the transmission of sensed data to a reader are both critical to enhancing the radio frequency energy harvester (RFEH) system's overall power conversion energy (PCE). Due to distance and other considerations such as the unavailability of precise and consistent power; consequently, the RF rectifier's design will need to be able to handle a broad range of input power with acceptable efficiency. This work presents a five-stage self-compensated charge pump rectifier in 4 different implementations with the application of the diode-connected MOS transistors technique to decrease the leakage current and the threshold voltage in reverse and forward operation regions respectively with the objectives to achieve high PCE dynamic range above 20% and 1V sensitivity by generating optimal compensation voltage using

auxiliary circuit. Each of these implementations has a unique auxiliary circuit that is designed to generate an optimal compensation voltage for each transistor in the main charge pump path, to convert RF signals to DC voltage efficiently. In comparison to conventional threshold voltage compensation circuits, where the level of compensation is restricted by the circuit construction and changes with input power, the proposed implementation achieves greater dynamic PCE throughout a wide input power range. This work is conceived and executed in a 130nm CMOS Silterra technology and obtained a broad range of 15 dBm with an efficiency of more than 20% and a sensitivity of -21 dBm for 1V output and a maximum PCE of 39.9% at -9 dBm of input power while driving a 1 MΩ load at 920 MHz.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
Sebagai memenuhi keperluan untuk ijazah Master Sains

REKABENTUK PENERUS PAMPASAN DIRI DENGAN LITAR TAMBAHAN UNTUK APLIKASI PENUAIAN TENAGA GELOMBANG RADIO

Oleh

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Berbilion-biloin peranti dilaporkan akan disambungkan ke internet melalui "Internet of Things" (IoT). Sebilangan besar alat ini, termasuk penderia tanpa wayar yang disambungkan secara tanpa wayar ke Internet, tidak akan mempunyai sambungan berwayar ke grid elektrik tetapi sebaliknya akan bergantung pada tenaga yang disimpan dalam bateri untuk beroperasi sendiri. Disebabkan oleh jangka hayat dan kekangan kapasitinya, sumber kuasa bateri menjadi penghalang untuk mengembangkan rangkaian penderia tanpa wayar kepada ratusan atau berjuta-juta nod, penuaian tenaga ialah kaedah praktikal untuk menghidupkan sekurang-kurangnya penderia dan peranti tanpa wayar tertentu. Memandangkan penuaian tenaga RF semakin tersedia, disepadukan dan juga serasi dengan rangkaian tanpa wayar, ia telah menjadi salah satu teknologi penuaian tenaga yang paling popular. Disebabkan oleh kehilangan laluan, pengecilan isyarat pantas pada jarak yang jauh, kecekapan kuasa bagi penukar RF-DC yang lemah, dan sekatan yang menyekat keamatan isyarat penyiaran tertinggi yang dibenarkan, penuaian tenaga RF sangat terkekang dalam keupayaannya untuk menangkap sejumlah besar tenaga. Walaupun rangkaian yang sepadan digunakan untuk meminimumkan kehilangan kuasa input yang diterima oleh antena dan meningkatkan pemindahan kuasa kepada penerus, transistor tidak boleh berfungsi pada tahap kuasa minimum yang diperlukan tanpa reka bentuk penerus yang berkesan. Peningkatan kecekapan penerus RF dan pengurangan penggunaan kuasa litar penderia dan pemancar tanpa wayar yang diperlukan untuk penghantaran data deria kepada pembaca adalah penting untuk meningkatkan keseluruhan tenaga penukaran kuasa sistem penuai tenaga frekuensi radio. Disebabkan oleh jarak dan pertimbangan lain, kuasa yang ada tidak tepat dan konsisten; akibatnya, reka bentuk penerus RF perlu dapat mengendalikan julat yang luas bagi kuasa input dengan kecekapan yang boleh diterima. Kerja ini mempersembahkan penerus pam caj pampasan sendiri lima peringkat dalam 4 pelaksanaan berbeza dengan aplikasi teknik transistor MOS yang disambungkan diod untuk mengurangkan arus bocor dan voltan ambang masing-masing dalam kawasan operasi songsang dan hadapan dengan objektif untuk mencapai julat dinamik PCE tinggi melebihi 20% dan sensitiviti 1V dengan menjana voltan pampasan optimum menggunakan litar tambahan. Setiap pelaksanaan ini mempunyai litar tambahan unik yang direka untuk menjana voltan pampasan optimum bagi setiap transistor dalam laluan pam cas utama, untuk menukar isyarat RF kepada voltan DC dengan cekap. Berbanding dengan litar pampasan voltan ambang konvensional, di mana tahap pampasan dihadkan oleh pembinaan litar dan perubahan dengan kuasa input, pelaksanaan yang dicadangkan mencapai PCE dinamik yang lebih besar sepanjang julat kuasa input yang luas. Kerja ini diilhamkan dan dilaksanakan menggunakan teknologi CMOS Silterra 130nm dan memperoleh julat luas 15 dBm dengan kecekapan lebih daripada 20% dan sensitiviti -21 dBm untuk output 1 V dan PCE maksimum 39.9% pada -9 dBm kuasa input semasa memacu beban 1 MΩ pada 920 MHz.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog-To-Digital Converter
AM	Amplitude Modulation
Ang.	Analog
CMOS	Complementary Metal Oxide Semiconductor
DAC	Digital-To-Analog Converter
dBm	Decibel Milliwatts
DC	Direct Current
Dig.	Digital
EM	Electromagnetic
FCC	Federal Communication Commission
GSM	Global System For Mobile Communication
IC	Integrated Circuit
IoT	Internet Of Things
ISM	Industrial, Scientific, And Medical
ITU-R	International Telecommunication Union Radio-Communication
KCL	Kirchhoff’s Current Law
KVL	Kirchhoff’s Voltage Law
MN	Matching Network
NMOS	N-Channel MOSFET
PCE	Power Conversion Efficiency
PEH	Piezoelectric Energy Harvesting
PMOS	P-Channel MOSFET

PMU	Power Management Unit
Ref.	Reference
RF	Radio-Frequency
RFEH	Radio-Frequency Energy Harvesting
RFID	Radio Frequency Identification
RMS	Root Mean Square
TCC	Temperature Coefficient
TV	Television
TX	Transmit
VDD	Supply Voltage
V_{th}	Transistor's Threshold Voltage
WLAN	Wireless Local Area Network
WPT	Wireless Power Transfer

CHAPTER 1

INTRODUCTION

1.1 Overview

Nowadays the “Internet of Things” IoT which is the expansion of internet connectivity of devices, is turn out to be a crucial subject due to given services and applications. The energy that powering up most of these devices comes from the energy stored in batteries. The battery power source is a limited due to its performance and lifetime, which could lead to operation interruption, maintenance requirements, and cost [1]. Designing a high-performance power supply generation for these types of devices, brings a challenge for the IC designers. Due to portable devices and the new generation, the electromagnetic field density is increasing and gives an excellent source to Radiofrequency (RF) Harvester. RF energy has around $0.2\frac{\mathrm{nW}}{\mathrm{cm}^2}$ to $1\ \mu\frac{\mathrm{W}}{\mathrm{cm}^2}$ energy density [2, 3]. Radio Frequency Energy Harvester (RFEH) has more advantages than the use of batteries. One of the valuable advantages is the unlimited lifetime and it can operate at any time as long as a minimum RF power is available [4]-[6]. The additional benefit of the RFEH system is the possibility of combination with solar energy harvesting or any other harvesting technologies [7]-[8].

1.2 RF Power Transferring Method

RF power transferring methods are divided into two major different methods, near field which is known also as wireless power transfer (WPT), and far-field [9]. Basically, in the far-field, energy harvesting is based on the energy received from the ambient signals such as AM/FM radio and cellular transmissions, and TV signals. Conversely, the near field has a higher power density with lower frequency compared to the far-field [10]. However, in the near field, magnetic and electric fields follow an illogical propagation law which contingent on its ambient nature and the type of supply antenna nature [11]. Near field radio frequency identification (RFID) systems are mostly used in wireless battery charging [12] and biomedical products [9].

1.2.1 The Frequency Band for RFEH System

As the GSM, 3G, and Wi-Fi have the licensed bands of frequency to operate, some unlicensed sections of the frequency range are adjusted for Industrial, Scientific, and Medical (ISM) purpose which is known as ISM bands. However, these bands are required to meet strict rules on the output power and the operation frequency, which are defined by the international telecommunication union radio-communication sector (ITU-R) [13]. The power restriction and on the

ISM bands is that the maximum effective isotropic radiated power (EIRP) is 36.99 dBm and the maximum power transmitter fed into the antenna, is 30 dBm [14]. Table 1.1 presents the ISM frequency band.

Table 1.1: ISM Frequency Bands.

Frequency Range	Centre Frequency	Bandwidth
(6.765-6.795) MHz	6.78 MHz	30 kHz
(13.553-13.567) MHz	13.56 MHz	14 kHz
(26.957-27.283) MHz	27.12 MHz	326 kHz
(40.66-40.7) MHz	40.68 MHz	40 kHz
(433.05-434.79) MHz	433.92 MHz	1.74 kHz
(902-928) MHz	915 MHz	26 MHz
(2.4-2.5) GHz	2.45 GHz	100 MHz
(5.725-5.875) GHz	5.8 GHz	150 MHz
(24-24.25) GHz	24.125 GHz	250 MHz
(61-61.5) GHz	61.25 GHz	500 MHz
(122-123) GHz	122.5 GHz	1 GHz
(244-246) GHz	245 GHz	2 GHz

The great RF ambient source will be in 900MHz to 950MHz and 22.45 GHz/ 5.8 GHz as these ranges use for mobile phones and local area networks, respectively [15].

1.2.2 Available Power for RFEH System

The available power is the power receives at the antenna that can be calculated based on Friis free space transmission [16]:

$$\boldsymbol{P_R = P_T G_R \frac{\lambda^2}{(4\pi d)^2}} \qquad 1\text{-}1$$

Where G_R is the gain of the receiving antenna, P_T is the transmitted RF power, λ is the wavelength and ***d*** represent the distance between receiver and transmitter. the wavelength is inversely proportional to the frequency ($\lambda \sim 1/f$), therefore the P_R decrease by $\frac{1}{d^2}$ and $\frac{1}{f^2}$. Figure 1.1 Demonstrates the free space path loss in dB scale versus distance for the two ISM band center frequencies of 2.45GHz and 915MHz.

As the distance double up the pathloss increases about 6dB. Based on the regulations of ISM in Malaysia, the maximum EIRP that can be transmitted in the band of 902-928 MHz is 36 dBm (4W) [14]. The path loss for the 915Mhz at a distance of 10m is about 51.6 dBm. Therefore, the maximum available power at a distance of 10m is less than -15.7 dBm, even due to multi-path fading, the available power is lower than this amount [17].

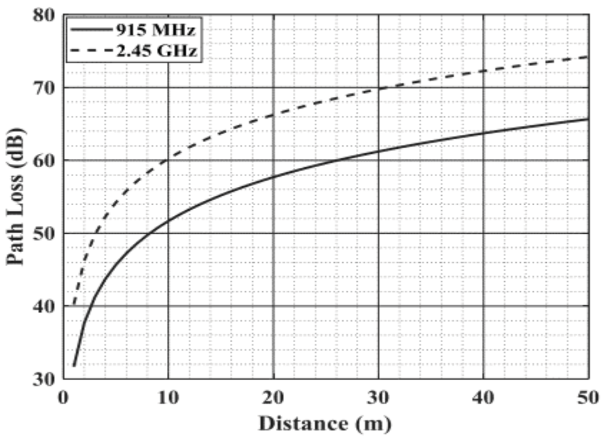

Figure 1.1: Free Space Path Loss.

1.2.3 Block Diagram of RFEH System

Figure 1.2 shows the block diagram of the RFEH system [18]. An antenna collecting the RF signal from the source, the matching network maximizes the power transmission to the RF rectifier and the RF rectifier is a converter that converts the RF signal from the matching network to a dc voltage. The power conversion energy (PCE) which is the ratio of the output DC power over the input AC power of the rectifier also its sensitivity, which is the lowest possible input power amount for starting a process are two main parameters to evaluate the performance of the RFEH system which are depending on the matching network and the RF rectifier efficiencies, However, RF rectifier plays the main role in the which becomes a real challenge for IC designers [19]. The PCE and sensitivity of the RF rectifier is extremely depending on the leakage current I_{leak} in reverse operation region and its threshold voltage V_{th} in the forward operation region of the RF rectifier [20].

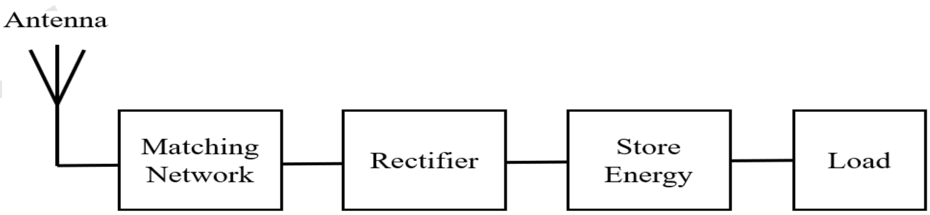

Figure 1.2: Block Diagram of The RFEH System.

1.3 Problem Statement

The general issue of the RFEH is the limited amount of energy that can be gained from the sources, as discussed, the RF available power at the antenna is lower due to the pathloss, multipath fading, and the limited maximum allowable signal strength due to the ISM regulations [13, 17]. Although a matching network is used to reduce the input power losses received by antenna and increase the power transfer to the rectifier, without efficient rectifier design, the minimum power level received at the antenna will not be sufficient to make transistors to operate, which reduce the sensitivity and Dynamic PCE range [35-43]. One of main issue of RFEH is incredibly low PCE, especially in the lower available power. Another issue is not constant available input power, due to matching loss and path loss and multipath fading [17]. Therefore, the RF rectifier should be able to function effectively over a wide range of input power. The optimum implementations are suggested by previous researchers however, their designs usually are unable to function effectively over a wide input power range.

By suggesting alternative diode-connected configurations or changing the gate-source voltages, also known as compensation voltages, which may be done by constructing an auxiliary circuit, a number of ways have been offered to achieve the high-efficiency rectifier. For instance, passive auxiliary circuits to supply compensation voltage were suggested by the authors in [38, 39], but their design's primary drawback in multi-stage application is the amount of space they take up. This is because there is a lot of resistance and capacitance being consumed, and there is also a lot of leakage current and high parasitic capacitance. In contrast, the inventors of [42] and [28] suggested active auxiliary circuits by coupling the gate terminals to the chain nodes that provide larger overdrive voltage. However, during the reverse biased operation, these methods experience substantial leakage current and inversion loss. A flexible connection is suggested in [43] to reduce leakage current and inversion loss. The primary flaw with these methods is that the compensation voltage is fixed and heavily reliant on input power. The gate terminals frequently fail to offer a high PCE over a large input power range because they are attached to certain nodes of the chain.

1.4 Aim of The Project

This work aims to design a highly efficient RF rectifier with great sensitivity to improve the overall PCE of the RFEH system. However, as the available power is not exact and constant, due to the distance and other factors, therefore the design of the RF rectifier will also cover a wide range of input power with acceptable efficiency. As a result, the thesis's objectives are classified as follows:

1. To design a self-compensated RF rectifier that cover a wide range of input power above 10dBm with acceptable efficiency above 20% at frequency of 920Mhz.

2. To design an auxiliary circuit that generates the optimal compensation voltage 0.35V.

3. To simulate and analyze the sensitivity of 1V and PCE dynamic range of the self-compensated RF rectifier designs while driving 1 MΩ, 500 kΩ, and 300 kΩ loads.

1.5 Project Scope

In this work, design of a single bound RF self-compensated rectifier to achieve great efficiency over a wide range of input power and the high 1V sensitivity will be presented. We first investigate what would be an appropriate compensation voltage to achieve this. Through mathematical derivation and modelling of circuits, we've determined the optimal compensation voltage level to get the highest PCE possible. Then, as a proof of concept, a five-stage, single-ended RF rectifier with a large input range and low power consumption is built to apply the transistors with the appropriate compensation voltage in order to demonstrate its feasibility.

The required threshold voltage compensation that maintains a reasonably constant value throughout a large input power range is achieved by a simple but effective construction that avoids the need of complicated auxiliary circuitry, external components, or baluns. As a result of the proposed threshold voltage adjustment, this design may deliver increased PCE and output voltage across a wider input power range compared to previously published designs. The suggested rectifier is conceived and implemented in four different methods in a standard 130 nm Silterra CMOS technology, with the results compared based on the post-layout simulations at 920Mhz frequency with off chip machining network.

1.6 Thesis Structure

The thesis is structured into 5 chapters.

Chapter 1 presents the motivation of the radiofrequency energy harvesting (RFEH) system and the major information related to the RFEH such as frequency bands and the available power to harvest. Also describes the main limitation of the RFEH system and briefly explains the possible solutions and the aim of the project.

Chapter 2 discusses the challenges of designing rectifiers at low power levels, as well as the limits of existing threshold voltage compensation approaches for rectifiers.

Chapter 3 discusses the design methodology in obtaining the optimum threshold voltage compensated rectifier circuit. The proposed rectifier is conceived and implemented in four potential methods in standard 130-nm CMOS technology.

Chapter 4 discusses the performance measurements of the four proposed implementations under a variety of input power and load conditions. A comparison of the proposed circuits' performance and most recent developments follows the identification of the best implementation through analysis and discussion.

In Chapter 5, the dissertation ends with an overview of important contributions and future-work

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

In order to improve the overall efficiency of the RF rectifier, the leakage current should be minimized, in this work the RF rectifiers are proposed in 4 different implementations with 2 different Model of transistor diode connections. By optimizing the significant number of stage and compensation voltage level, the charge pump is able to generate wide dynamic PCE range above 20% for 5 stages charge pump with compensation voltage about 0.3V to 0.4V.

An auxiliary circuit is proposed as a voltage divider to provide the threshold voltage compensation for each transistor at the main charge pump. Then, three different implementations are proposed which they are different in the high impedance paths of the auxiliary circuit. The auxiliary circuits are tuned and sized in order to generate the compensation voltage near to the optimum range of compensation voltage.

After simulation of the auxiliary circuit, the generated compensation voltage for all implementations is varying slightly averagely about 40mV as input power changes from -21 dBm to -5 dBm and even load varies from 300k to 1M. which means all implementations are able to generate nearly consistent compensating voltage regardless to the input power and loads.

All four implementations are constructed in 130-nm SilTerra CMOS technology. The post-layout of these implementations are simulated and analyzed for various factors such as Dynamic PCE range, peak efficiency, sensitivity, and area consumption, and found that Implementation 3A had the greatest overall performance when compared to the other implementations.

In contrast to earlier research, Implementation 3A achieves a virtually average constant peak efficiency of roughly 39% for 1 MΩ, 500 kΩ, and 300 kΩ output loads, and a large dynamic PCE range of around 20% for all of these loads. Without a differential antenna or PCB balun, as well as specific CMOS transistors and a significant number of stages, implementation 3A has a sensitivity of -21 dBm at 1 V.

In this work, a self-compensated RF rectifier with a simple structure to provide the best compensation voltage has been proposed and the design is capable of providing almost constant compensation voltage for all input power while driving various output loads. At -9 dBm of input power, the proposed rectifier achieves a maximum PCE of 39.9% while driving a 1 MΩ load. For an input power level of more than 15 dBm, the measured PCE stays over 20%. The proposed circuit has a sensitivity of -21 dBm for generating 1 V over a 1 MΩ load while requiring just 0.087 mm^2 of silicon area.

5.2 Future Work

Matching networks are crucial for attaining maximum PCE for RF energy harvesters because the matching network not only makes it easier to transport power from the antenna/coil to the rectifier, but it also enhances the rectifier's input voltage to surpass the threshold voltage. Optimal matching networks for RF energy harvesting systems will be the focus of future research, and a systematic approach to constructing impedance matching circuits for RF energy harvesters will be proposed in order to optimize the harvested energy. A high-efficiency 5T-cell rectifier will be developed using the optimum threshold voltage compensation approach that we've described. In the future, harvesting energy from a variety of frequencies is also possible. Harvesting energy from various frequency bands simultaneously increases output power. Microstrip antennas and high-Q matching networks have a limited bandwidth by design. For these reasons, we are aiming to construct a microstrip antenna and matching network with a very small bandwidth at each band in order to harvest energy from diverse frequency ranges.

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