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RF and Piezoelectric Energy Harvester by applying a Threshold Voltage Rectifier Cancellers

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Thesis submitted in partial fulfillment of requirements of the degree

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Signature page

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by ([Hashem M. H. Abu Aram)

ABSTRACT

In this thesis study about the RF are shown and Piezoelectric Energy Harvester and focused on the problems of using rectifier circuit represented by: threshold voltage higher than input voltage, Reverse current from the storage damage the current rectifier, to improve the efficiency of the system, anew rectifier circuit that reduce the drop voltage were proposed, and protection the reverse current with hybrid energy harvesting from RF and piezoelectric to provide DC voltage and improve the system. The simulation results showed an increase efficiency of rectifier circuit to 41.7% compared to the efficiency reached by researchers previously and The voltage reaches stability in a brief period of time, which is estimated to be nanoseconds. Those two points were an obstacle in the path of researchers previously, those problems are solved, and then energy from many sources could collect to power any smart system.

[حاصدة الترددات الراديوية والطاقة الكهر ضغطية عن طريق تطبيق عتبات مقوم الجهد]

هاشم محمد ابو عرام

الملخص

في هذه الأطروحة ، تم عرض دراسة حول RF وحاصدة الطاقة الكهرو إجهاديه وتركز على مشاكل استخدام دارة المعدل المتمثلة في: عتبة الجهد أعلى من جهد الدخل ، والتيار العكسي من ضرر التخزين ، مقوم التيار ، لتحسين كفاءة النظام ، تم اقتراح دائرة مقوم جديدة تقلل من انخفاض الجهد ، وحماية التيار العكسي مع حصاد الطاقة الهجين من الترددات الراديوية والكهرباء الانضغاطية لتوفير جهد التيار المستمر وتحسين النظام. أظهرت نتائج المحاكاة زيادة كفاءة دارة المقوم إلى ٤١.٧٪ مقارنة بالكفاءة التي وصل إليها الباحثون سابقاً ووصل الفولتية إلى الثبات في فترة وجيزة تقدر بالنانو ثانية. كانت هاتان النقطتان عقبة في طريق الباحثين سابقًا ، فقد تم حل تلك المشكلات ، ومن ثم يمكن أن تتجمع الطاقة من العديد من المصادر لتشغيل أي نظام ذكي.

DECLARATION

I declare that the Master Thesis entitled " Hybrid Harvesting Energy" is my own unique work, and herby guarantee that except if expressed, all work contained within this thesis is my own independent research and has not been submitted for the award of some other degree at any institution, aside from where due acknowledgment is made in the content.

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الاهداء

الى الذين عبدوا لي طريق الحرية

فكانوا بحق مشاعل نور ونار أضاءت

كل حرف من حروف هذه الرسالة

الى والدي العزيز

الى والدتي الكريمة

الى زوجتي الفاضلة التي كانت معوانا لي في هذا الدرب الطويل , ما هانت , ولا استكانت .

الى ابنائي الاحبة: ريماس , محمد , صهيب

الى الاخوة الكرام والعائلة الكريمة

الى شهداء الوطن العربي الذين خضبوا بدمائهم الزكية ثرى هذا الوطن الطاهر كي يتحرر من براثن الاحتلال

ويسطع شمسه في رابعه النهار

الى كل هؤلاء اقدم هذا الجهد المتواضع كي يكون منارة للاجيال القادمة علها تتوحد تحت راية الوحدة العربية المنشودة

الشكر والتقدير

.

الحمدُ لله الذي بنعمته تتمُ الصالحات الحمد لله ما انتهى درّب ولا ختم جهد ولا تم سعي إلا بفضله الحمدُ لله على البلوغ ثم الحمدُ لله على التمام والحمدُ لله من قبل ومن بعد تم بحمد الله الانتهاء من كتابة رسالة الماجستير وانني لم اكن منجز هذا العمل لولا فضل الله اولا علي ثم من وقف بجانبي وساعدني من من ساندوني واتقدم بالشكر والتقدير الجزيل لكل من الأستاذ الفاضل د.غاندي مناصرة والدكتور سمير حنا على ما قدموه لي من علم نافع وعطاء متميز وارشاد مستمرو ساعدوني ووجهوني نحو النجاح ومهما كتبت من عبارات وجمل فإن كلمات الشكر تظل عاجزة عن إيفاء حقهم فجزاهم الله كل خير وجعله في ميزان حسناتهم

إليك يا من كان له قدم السبق في ركب العلم والتعليم، إليك يا من بذلت ولم تنتظر العطاء، إليك أهدي عبارات الشكر والتقدير و الامتنان إلى والديّ العزيزين اللذين غرسا حب العلم فيّ من الصغر, وقدما لي كل غالي ونفيس, وكان لهما الفضل بعد الله فيما وصلت إليه الآن فلا أملك إلا الدعاء لهما بطول العمر وحسن العمل وبلوغ الجنان. واتقدم بجزيل الشكر لزوجتي الغالية لمساعدتها لي في اعمال التنسيق والطباعة .و أتقدم بالشكر الجزيل لكل من ساعدني و قدم لي يد العون و كل من كانت له اسهاما صغيراً او كبيراً, و أسدى لي معروفًا, أومد لي يد العون في إنجاز هذا العمل , أو قدم لي نصيحة, فله مني خالص الشكر والتقدير.و نحمد لله حمد ا كثير طيبا مباركا و الحمد لله رب العالمين , عدد خلقه ورضا نفسه وزنة عرشه ومداد كلماته, والصلاة والسلام على نبي المرسلين محمد ﷺ , وعلى آله وصحبه أجمعين.

List of Abbreviations

CMOS	Complementary Metal Oxide Semiconductor
dBm	Decibel-milliwatts
FET	Field-Effect Transistor
GSM	Global System Mobile
Li-Po	Lithium Ion Polymer
ME	Mechanical Energy
Ni-MH	Nickel Metal Hybrid
NMOS	Negative Type Metal Oxide Semiconductor
PCE	Power Conversion Efficiency
PMOS	Positive Type Metal Oxide Semiconductor
RF	Radio Frequency
RFID	Radio-Frequency Identification
SE	Solar Energy
SVC	Self-Threshold Voltage Cancellation
TE	Thermal Energy
VCE	Voltage Conversion Efficiency
WLAN	Wireless Local Area Network

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CHAPTER 1

INTRODUCTION

Energy harvesting gives a promising future to supply energy from different ambient sources. Energy scavenging, Power Harvesting, and energy harvesting got from sustainable power [1].

Energy Harvesting is the way toward catching minute amounts of energy from one or more of normally getting energy sources, accumulating and storing them for some time in the future. Energy harvesting has many sources; Light or sun oriented Energy (SE), mechanical energy (ME), Thermal Energy (TE), Ambient Energy (AE) and Other Energy - from chemical and organic sources, Electromagnetic or radio frequency RF Energy (RFE).ME is the primary one, which can be gotten from vibration, mechanical anxiety. ME conversion is employed in hydroelectric and wind turbines for large-scale generation to satisfy the demands of urban communities. TE can be acquired from squander energy from heaters, furnaces, and rubbing sources. TE transformation is a technology being worked on.SE is collected from sunlight or light source by means of photo sensors, photo diodes, or sun powered boards (solar panels). In this platform the sunlight based energy is changed over to electrical energy. Sun based farms give electrical generation on a large cites scale just as for singular home proprietors.RFE can be produced from inductors, coils and transformers. Electromagnetic energy in the millimeter (mm) is changed over to micron-wavelength scope of the electromagnetic spectrum to electrical energy.AE can be generated from the environment such as wind, water stream, sea ebbs and flows, and solar, human body - a mix of mechanical and thermal energy normally produced from bio-organisms or through activities such as strolling and sitting [2,3].

To be sure, energy harvesting is the change of environment energy to electrical energy to be utilized in fueling electronic gadgets or circuits. All things considered, this change is identical in essence to large-scale renewable energy generation like wind turbines. However, the amount of energy created is much smaller, being commonly many micro watts to a few watts. Energy harvesting can be utilized to give an option in contrast to batteries. Whilst batteries are minimum cost, they contain a finite amount of energy and need occasional replacement or recharging.

The removal of batteries is also an environmental concern and, as autonomous systems multiply, this worry can develop quickly [4].

In general, an energy harvesting system comprises of the accompanying components , energy source ,transducer to changing over ambient energy into electrical energy, energy stockpiling component, which regularly a rechargeable battery or a capacitor, is utilized to store the harvested energy and Power electronics which has many functions; conditioning the harvested power, maximizing the amount of stored energy, and managing the power flow to the system load that it's connected,[5,6] see figure 1.1 shown block diagram for components of energy harvesting system .

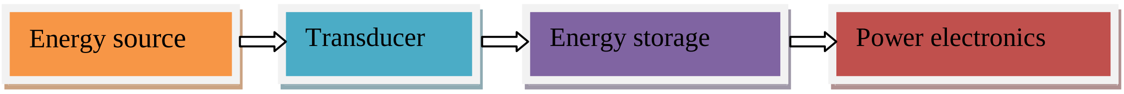


Fig. 1.1 block diagram for components of energy harvesting system.

This chapter gives a prologue to energy harvesting from two sources (radio frequency (RF) energy harvesting and piezoelectric energy harvesting). However, every kind of electronic devices and applications, from laptops, mobile, small watches, small power apparatuses, required an outer electrical power sources or batteries. Therefore, energy harvesting can produce small amount of electrical power which may be accumulating and storing them for later use.

1.1 Radio Frequency (RF) Energy Harvesting

RF energy harvesting from the space can generate small amount of electrical energy which may be suitably used or stored. Radio waves are wide spread in our life, it has many various source of signals according to electromagnetic spectrum; Television, mobile phones, radio, WLAN etc. Difference RF sources are shown in Figure 1.2 [1].

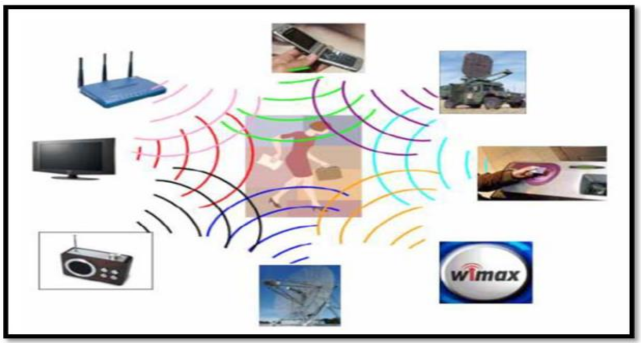


Fig. 1.2 Difference RF sources [1].

Nowadays, wireless devices are filling in multi applications like sensor networks or mobile phones. In that case, the use of batteries will be increased. Many research teams are performing on the autonomy of the batteries by reducing the consumption of the devices. Others teams have chosen to recycle ambient energy. Some sources of RF systems has very low power density levels such as mobile networks or WLAN bands [7].

System components for RF energy harvesting the idea of RF energy harvesting system is shown in Figure 1.3 which comprises of power source (or radiating system), a matching network, Voltage multiplier – which is used to perform conversion from RF signal to DC power- and load circuits or storage.

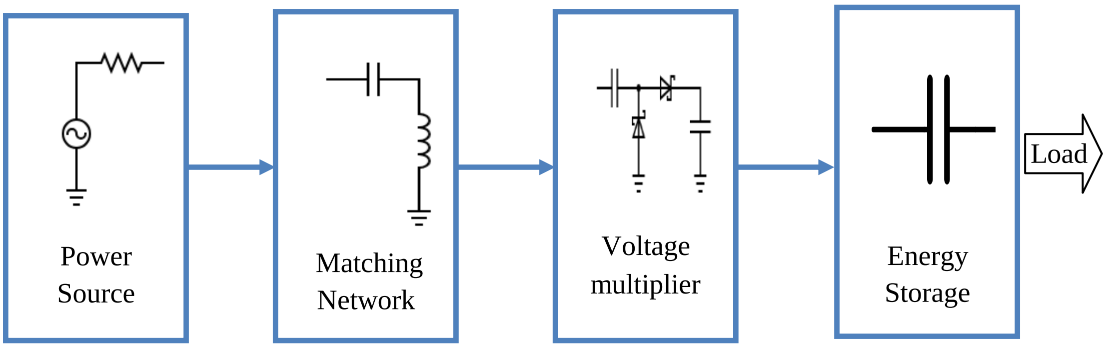


Fig. 1.3 shows the components of our proposed radio frequency (RF) energy harvesting system.

The RF energy harvesting can be converted from AC to DC by using voltage multiplier and when it increase the number of multiplier stage gives higher voltage at the load or battery, the matching circuit contain inductive and capacitive element to ensure the energy harvesting from antenna to voltage multiplier without any reflection of the energy, and energy storage is backup to provide the load when the external energy is not available [8].

1.1.1 Source RF Energy Harvesting

The power source of RF can be compile from the environment by using antenna. The input signal is very small AC signal with rang frequency between 20kHz – 300 GHz. for example radio frequency can be used in energy harvesting GSM, Wi-Fi, television (TV), and wireless local area networks (WLAN) [9].

The RF power density measurements can be performed in various focuses in the metropolitan environments. The variety of this density in dBm/m² (decibel-milliwatts is a unit of level used to indicate that a power level is expressed in decibels (dB)) relies upon the time and frequency in the 680MHz-3.5GHz band. The power density variety is discovered to be - 60dBm/m² to - 14.5dBm/m²or by using watt peer meter square is 1nW/m² to 35.5μW/m². As can be seen from Figure 1.4, GSM 900/1800 MHz bands have high RF power densities. consequently the accessible voltage in the input terminal of Radio-frequency identification RFID antenna is very small approximately less than 300 mV [3,10].

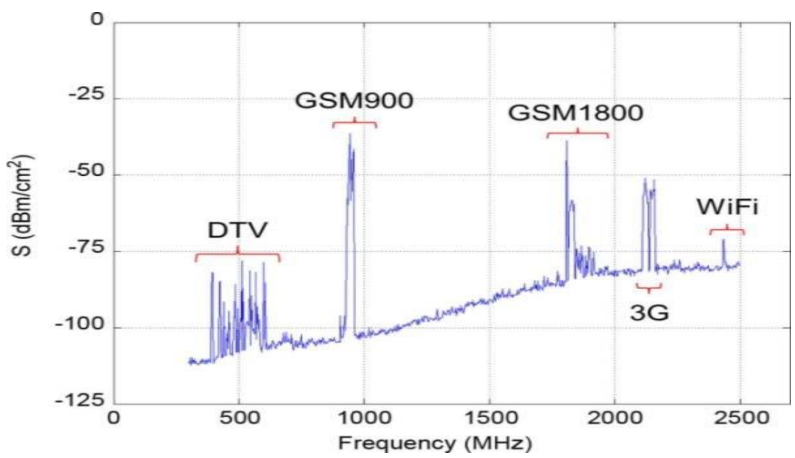


Fig. 1.4 Typical RF power densities [9]

At the higher frequency, the values of inductor cannot be constructed in circuit design. In that case, we can use capacitor along with inductor at integrated circuit design in order to improve the performance .Resonant frequency is likewise affected by diode capacitance as it is related with input voltage and reverse diode voltage[11].

1.1.2 Matching Network for System RF Energy Harvesting

Antenna receives in RF energy harvesting consists of both resistive and reactive component so the impedance of the antenna must equal input impedance for rectifier circuit. To solve this part we can use matching circuit or input impedance to rectifier circuit the same output impedance of the antenna [12]. A matching network is connected between a Voltage multiplier and a source. It's circuitry is normally designed to transfers almost all electric energy to the Voltage multiplier while introducing an input impedance Z_{in} is equivalent to the complex form of the source's and output impedance Z_{out} is equivalent to the complex form of the Voltage multiplier [11].RF configuration is about impedance matching. Inductors and capacitors are handy elements at impedance matching Figure 1.5 as shown matching circuit.

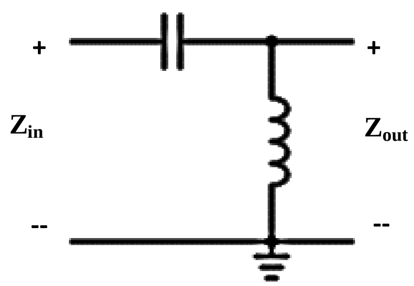


Fig. 1.5 Matching Circuit

If the source impedance is purely resistive and the Voltage multiplier with load impedance is of complex type, then a complex conjugate of the Voltage multiplier impedance would be required for the matching network. The impedance for the antenna is not constant because the impedance of capacitive and inductive deepened on the frequency so in manufacturing the impedance for the antenna is 50 Ω at one specific frequency , but if the antenna receive at different frequency the impedance of the antenna will change, so that the system mismatch [12,13].

1.1.3 Multiplier Voltage for System RF Energy Harvesting

The impedance matching circuit between the reception apparatus (antenna) and the rectifier circuit is important to reduce the reflection and increase the voltage gain .The main aim for rectifier circuit to change input signal AC to DC and satisfy after correction maximum amount of energy and reduce the power loss, but when the input energy is low then the rectifier proficiency is low so we need to improve the rectifier circuit to improve the efficiency [14].

The Radio Frequency is AC signal, so the rectifier circuit use to get a DC from the input AC signal. The voltage multiplier structure is the same full wave rectifier considered for RF-DC power conversion system because it rectifies peak-to-peak voltage from the input RF signal AC. So can be used Schottky diode to create voltage multiplier show in figure 1.6 , Schottky diode consider as an ideal component for RF energy harvesting, also it is offer low forward voltage and high switching speed [11,14].

Figure 1.6 shown one stage of the circuit at negative half-cycle of the voltage stored on C1 and in positive half-cycle the voltage stored on C_2 from C_1 and positive half-cycle. Thus, the voltage on C_2 equal double input voltage from the negative signal of RF source and double threshold voltage, hence the name voltage multiplier or doubler [15].

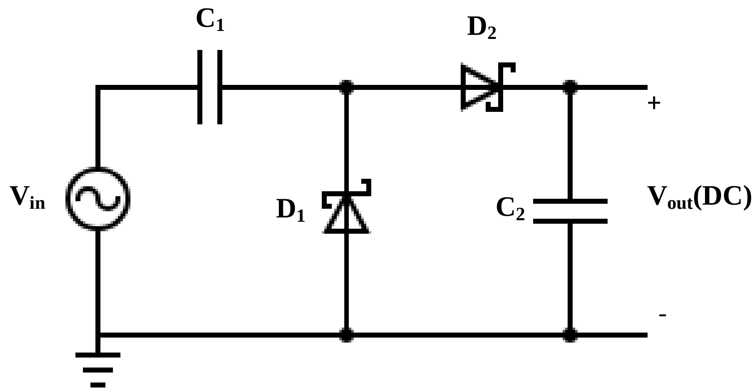


Fig.1.6 One Stage of the Voltage doubler

To increase the output voltage by using n-stage of multiplier and the output of one stage is not exactly DC, it is contain noise show in figure 1.7. If the second stage is add on the first stage, the output voltage signal will doubled from the noise and DC, so that n-stage that mean, the output voltage is equal n input voltage [15].

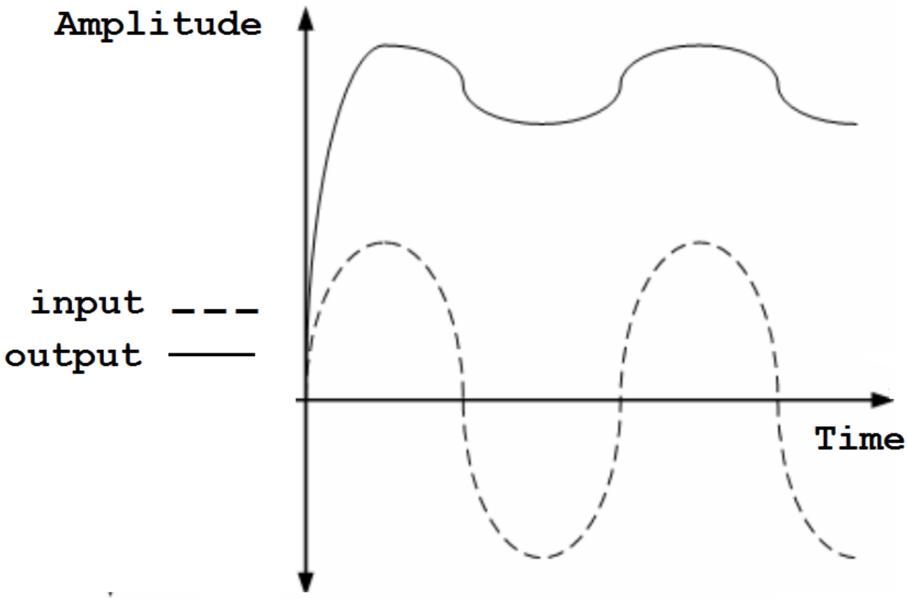


Fig. 1.7 Voltage Multiplier Waveform

The energy storage device can be used a battery whether it is non rechargeable or rechargeable. A non-rechargeable battery (e.g., alkaline) is suitable for very low power consumption micro sensor (e.g., 50 μW), while rechargeable battery (e.g., lithium ion) is used widely in sensor nodes with energy harvesting technology. A battery is used storage of energy generated and it is used to regulate the supply of energy to small application [16].

There are as of now two main technologies for energy stockpiling: super capacitors and rechargeable batteries. The super capacitors have higher power density however lower energy density than the rechargeable batteries. This means that they can't store the same amount of energy, however they can transfer power at a much more prominent rate than batteries, making them appropriate for short handling [6].

1.2 Piezoelectric Energy Harvesting

Piezoelectric Energy Harvesting is generate electrical energy from mechanical energy. When apply force on the piezoelectric produce electrical charge and when apply electricity on material of piezoelectric produce vibration also, the output energy from this material is very small application and the electrical energy can be storage in rechargeable battery or super capacitor [17].The material of Piezoelectric possess crystal structures within which the centers of negative and positive charges don't interfere, resulting in bipolar moments. At exposure to mechanical motion or vibrations, it is can be applied to these materials and causes the dipoles to deform, leading to an electrical charge. Piezoelectric materials comprise four classes supported structure properties: single crystals, ceramics, composites, and polymers. [18,19]

Electro-vibrational energy harvesting utilizing piezoelectric impacts has been investigated for likely use in sensor network units. In order to get energy from the environment, it's important to get vibrations of frequencies under 200 Hz, in light of the fact that these frequencies are common in standard life and in vehicles, as show in Table 1 [20,22].

Table 1.1. Frequency and acceleration of the vibration sources in the environment [22].

Origin of the vibrations	Acceleration (m2/s)	Frequency (Hz)
3-Axis machine	10	70
Cooking mixer	6.4	121
Clothes dryer	3.5	121
Electric oven (small size)	2.25	121
Air exhaust in buildings	0.2-1.5	60
Wood deck with traffic	1.3	385
Windows facing busy street	0.7	100
Note PC loading CD	0.6	75
Washing machine	0.5	109
Refrigerator	0.1	241

Figure 1.8 shown block diagram of piezoelectric energy harvesting systems Which consists of Mechanical Noise Vibration, Piezoelectric Material, Energy harvesting circuit (AC-DC) and Energy Storage or Load. Energy harvester is vibrated by the excitation power of the vibration source, then the mechanical energy is changed over to electrical energy by utilizing piezoelectric in energy harvester [20,21].

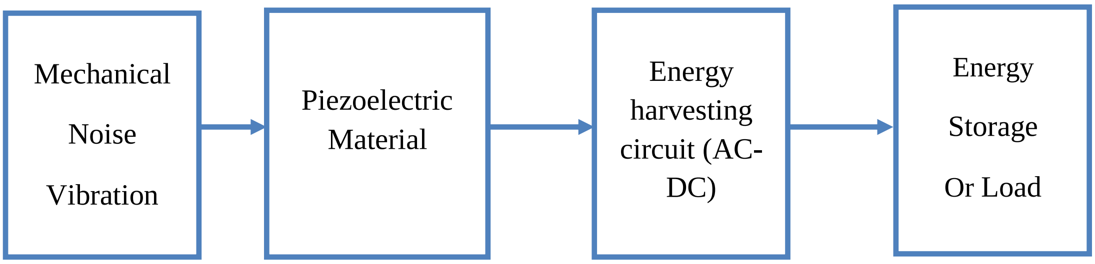
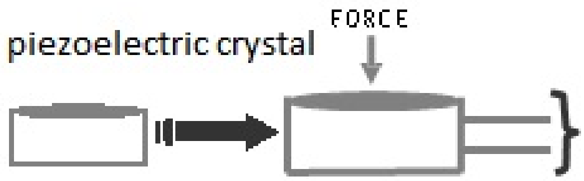


Fig. 1.8 block diagram for components of piezoelectric energy harvesting.

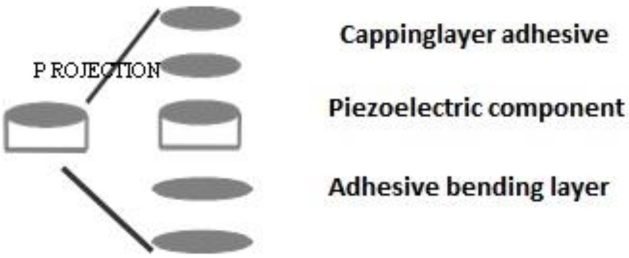
1.2.1 Piezoelectric Material

Piezoelectric materials are unmistakably utilized for harvesting energy from environment sources of vibrations, since they can effectively change over mechanical pressure into electrical charge without any extra energy and they have a simple mechanical structure. They additionally have a few points of interest over other alternative technologies such as: huge energy density, simplicity of utilizations, and the ability to manufacture at different scales: macro, nano and micro scale [18,23].

The idea will be clear from the diagram shown in Figure 1.9 which shows the structure of the piezoelectric parts that utilized for energy harvesting. The output voltage generated from a single piezoelectric crystal is in the mil-volt range, which shifts with various crystals and the wattage is in the microwatt range. Therefore, in order to achieve a higher voltage, the piezoelectric crystals can be orchestrated in an arrangement, i.e. in the sequence [24].



(a)

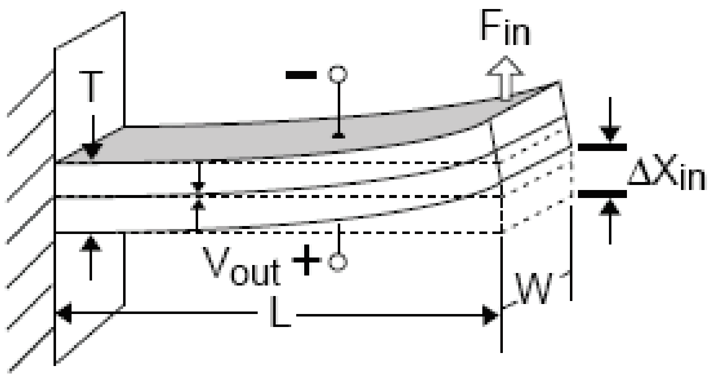


(b)

Fig. 1.9 : (a) Principle of direct piezoelectric effect. (b) Structure of a piezoelectric component [24].

In previous studies, the tapered shape was the best designing to improve the output power; while most business examples has rectangular shape for simplicity of production. Piezoelectric structures have platforms such as: unimorph, bimorphs, multilayered chimneys, s-morphs, rainbows, cymbals and Moonie. The most platform used in applications is the two-shape. The bimorph is a cantilever that comprises of a meager metal layer in the middle of two piezoelectric slender layers.

In figure 1.10 shown the piezoelectric monorail has an active (or piezoelectric) layer and a single inactive (or non-piezoelectric) layer. The Bimorph cantilever comprises of a focal wafer covered between two piezoelectric layers. This construction has advantages such as improve mechanical strength, reduce movement, which improves safety. A Bimorph cantilever creates a more prominent yield voltage than a unimorph stage and is ordinarily utilized [23].



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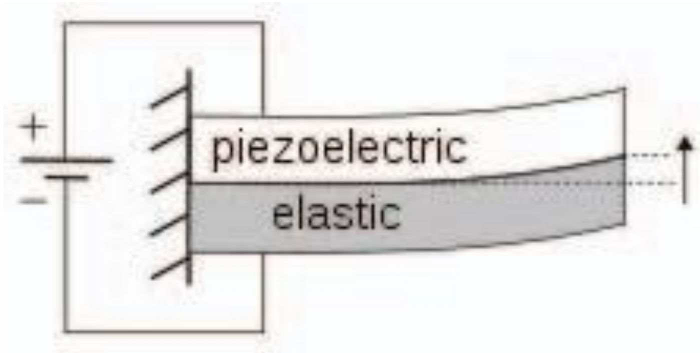

(b)

Fig. 1.10: (a) Bimorph energy harvesters. (b) Unimorph energy harvesters [23].

1.2.2 Rectifier circuit (AC-DC) for Energy harvesting

The main goal of rectifier circuit is to convert input voltage AC to DC signal. Different types of rectifier may be used such as half wave bridge rectifier diode, full wave bridge rectifier diode and voltage multiplier. The problems for any rectifier circuit at input low voltage due to threshold voltage (voltage drop) at the forward biased of the diodes and the leakage current when the diodes are reveres current (reverse biased). So, that is an important to select diodes with a low reveres current and low voltage drop. The voltage multiplier structure is the same full wave rectifier and to satisfy after rectification maximum efficiency at improvement rectifier circuit [20,23].

The output Piezoelectric Material is AC signal, so the rectifier circuit use to get a DC voltage at the output from the input AC voltage, Figure 1.11 shown a correction circuit with a full wave rectifier, the capacitor is utilized for storage electrical energy of the piezoelectric materials.

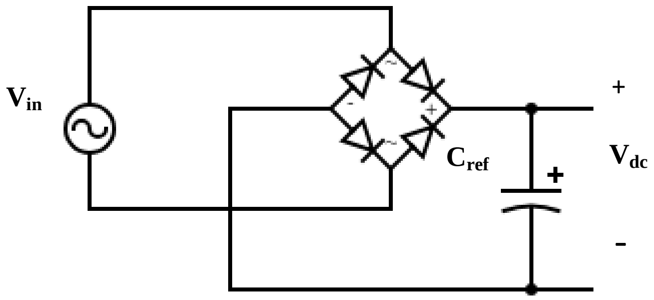

Fig. 1.11 showsa full-bridge rectifier for piezoelectric energy harvesting.

After rectifier, the voltage output from piezoelectric component still needs to be regulated for external energy storage device or load. There are two sorts of voltage regulators commonly utilized in step down and step up transformers for power harvesting, There are two sorts of voltage controllers regularly sync up and venture down transformers for power harvesting, and among them the first type is the most utilized because the output voltage of the piezoelectric components is usually high relative to electronic load or the battery [18].

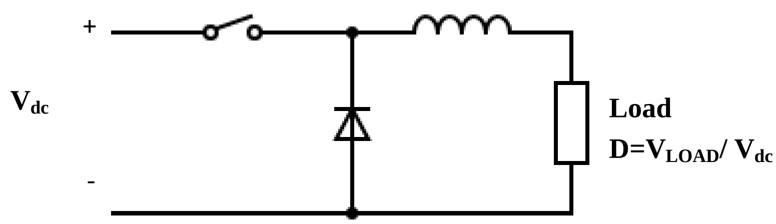

Fig. 1.12 shows Buck-boost DC-DC Converters.

Figure 1.12 shown the DC-DC converters have different topologies such as: boost (step up), buck (step down) and buck-boost (step up and step down). The boost transformer is best suited for high efficiency and for low excitation levels, and works at an input voltage lower than the output voltage. Assume no losses power and proceeded with activity mode as the operating ratio (D) is somewhere in the range of zero and one ($0 \leq D \leq 1$), the boost transformer will increase the voltage. The boost transformer is used to improve the low voltage level of direct current of the bridge rectifier [23].

1.3 Objective of the Thesis

The main objective of this thesis is to collect the energy harvesting from radio frequency and vibration of the environment and then rectifier energy harvesting from AC to DC voltage by using voltage multiplier and regulated to provide the load or storage. The energy harvesting is very small so the second idea improves the rectifier circuit to improve the efficiency. The last objective is to hybrid energy harvesting from RF and piezoelectric to provide DC voltage for any small application at any time.

1.4 Contribution

The contribution of the thesis is to improve the efficiency rectifier circuit by solving the threshold voltage drop problem, and to reverse current from the storage to system rectifier, and to increase the power at any time. Hybrid system can be used to collect energy harvesting from two sources RF and piezoelectric.

1.5 Organization

This thesis is coordinated as follows, the past investigations finally years were talked about in chapter 2. System postulation contain theoretical background, basic components, methods and techniques of the proposed rectifier energy harvesting is talked about in chapter 3. Problem formulation and systems modeling are discussed in chapter 4. In chapter 5, we present the simulation results of the rectifier circuits discussed in chapter 4. Future work and conclusions will be discussed in chapter 6.

CHAPTER 2

LITERATURE REVIEW

In last ten years, energy harvesting has been a focus of the research community. The most important thing was the possibility to get it from radio frequency and piezoelectric energy, knowing that it is very small and should collect without any loss with high efficiency.

In [2] design and development of energy harvesting devices for wireless power transmission isto help solve the energy problems by directly harvesting emitted energies from electromagnetic radiation. RF energy harvest and storage system of rectenna In [1] a discussion of various varieties rectennas (antenna + rectifier) that is employed for various variety of RF energy harvest home close signals and storage system. Present a study of close RF energy harvest in [5] this techniques by measuring of the close RF power density is conferred, and with two systems are studied to recover the RF energy however the energy terribly little in order that use battery to gather the energy. RF energy harvesting In [25] the levels of power which will be harvested from the encompassing atmosphere and processed to attain levels of energy that area unit sufficient to charge tiny electronic circuits, and devices by mistreatment small strip antenna within the receiver section to receive the facility harvest from the transmitter . RF energy is more responsible ohmic resistance matching circuit and voltage multiplier factor circuit to urge a resultant voltage. Design of piezoelectric energy harvest and storage devices In [21] the piezoelectric power harvesting is a very important concept in renewable power, and the power generated by a piezo ceramic is ac output signal and cannot used directly in battery charging so we need rectifier circuit. Design considerations for piezoelectric energy harvesting systems In [23] This paper focuses on the design concerns for piezoelectric energy harvest systems such as: material choice, resonant frequency, geometrical form, loading issue, electrical connections, AC-DC converters, DC-DC converters, and energy storage. Energy collection via piezoelectric In [24] it is mechanical energy harvest utilizes piezoelectric elements wherever deformations made by completely different suggests that area unit directly regenerate to electrical charge via piezo effect.

RF energy harvest system and circuits for charging of mobile devices In [26] This paper presents the summary and progress achieved in RF energy harvest field. A modified form of existing CMOS based voltage doubler circuit is presented to achieve more efficiency. High efficiency RF to dc convertor with reduced escape current for RFID applications In [17] this thesis a high efficiency RF to DC convertor for RFID applications. The projected circuit has been designed in ninety nm CMOS technology employing a single RF supply. Dickson charge pump rectifier using ultra-low power (ULP) diode for BAN Applications In [10] in this paper Rectifier converts ambient RF into direct current (DC) by using Complementary Metal Oxide Semiconductor (CMOS) technologies which restrict their usefulness in low-cost applications. Hybrid Internal V_{th} Cancellation Rectifiers for RF Energy Harvesting In[27]However, from the previous study we need to improve the voltage multiplier circuit to improve the efficiency and develop the system compile the energy harvest from two source RF and piezoelectric hybrid energy harvesting.

CHAPTER 3

PROBLEM FORMULATION AND MODELLING

The Radio Frequency (RF) and Piezoelectric Energy Harvesting produce small energy that can be used directly to operate the devices or store them in batteries. But when the amount of energy is very small, The Energy Harvesting is AC voltage signal, to get a DC voltage from AC signal, we need rectifier circuit and it needs Voltage Multiplier in several stages so that we can store it again in batteries or use it for devices directly.

The electrical circuits used consume a quantity of energy, so we will work to raise the efficiency and reduce energy losses of the system so that we can combine the energy from The Radio Frequency (RF) and Piezoelectric Energy Harvesting. There are two classifications of rectifiers, talked about in 3.1 and 3.2.

3.1 Diode Based rectifier and Multiplier circuit

The voltage multiplier rectifier topologies, including the Villard voltage multiplier and the Dickson topology rectifier have been reviewed. The voltage multiplier consists of a series of voltage doublers AC-DC. The voltage doubler comprises two capacitors and two diodes [10], as shown in Figure 3.1

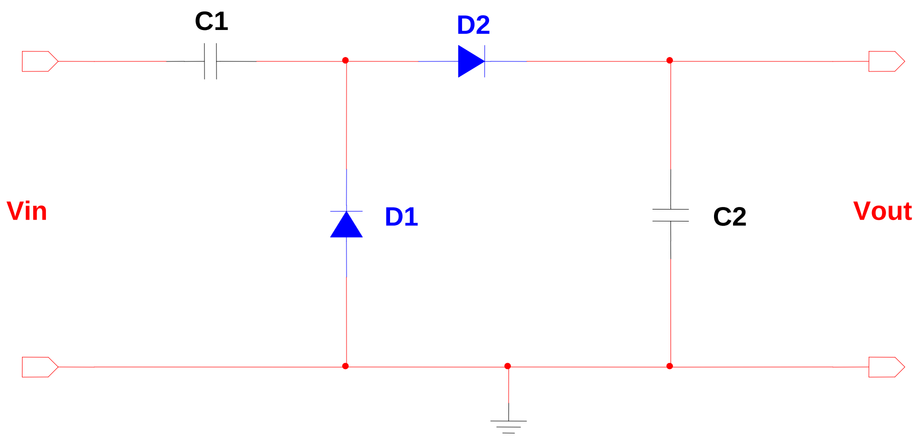

Fig. 3.1: A one-Stage Dickson and Villard Voltage doublers Circuit

The voltage doublers (voltage multiplier)consists of a series of voltage multiplier AC-DC. each stage for The voltage multiplier comprises two diodes $(D_1 - D_2)$and two capacitors $(C_1 - C_2)$ If we assume that the diodes are ideal, let us assume initially $(C_1 = C_2)$, $V_{C2} = 0$, and $V_{C1} = 0$, then the threshold voltage is zero, and let input voltage AC is V_{in},This circuit serves to change the AC - DC signal. When the AC signal is in a negative cycle$(-V_{in})$, the diode D_1 is forward biased and diode $D_2$is in reverse biased. The current will flow into C_1 and charge it until the voltage rise to V_{in} .Thus, when an AC signal is in a positive cycle$(+V_{in})$, diode D_1 is in a reverse biased and the diode D_2 is forward biased. Then, the current will flow into C_2 through D_2. The current into C_2 is not only derived from the voltage source V_{in} $(peak)$, but also fromC_1. Thus, the output voltage from energy harvesting is twice of the voltage source.

$$V_{C1} = V_{in(peak)} \quad .... \; 3.1$$

$$V_{C2} = V_{C1} + V_{in(peak)} = 2\,V_{in(peak)} \quad .... \; 3.2$$

$$V_{out} = 2\,V_{in(peak)} \quad .... \; 3.3$$

The n-stage diode-based Dickson voltage multiplier is shown in Figure 3.2 and The n-stage diode-based Villard voltage multiplier is shown in Figure 3.3.

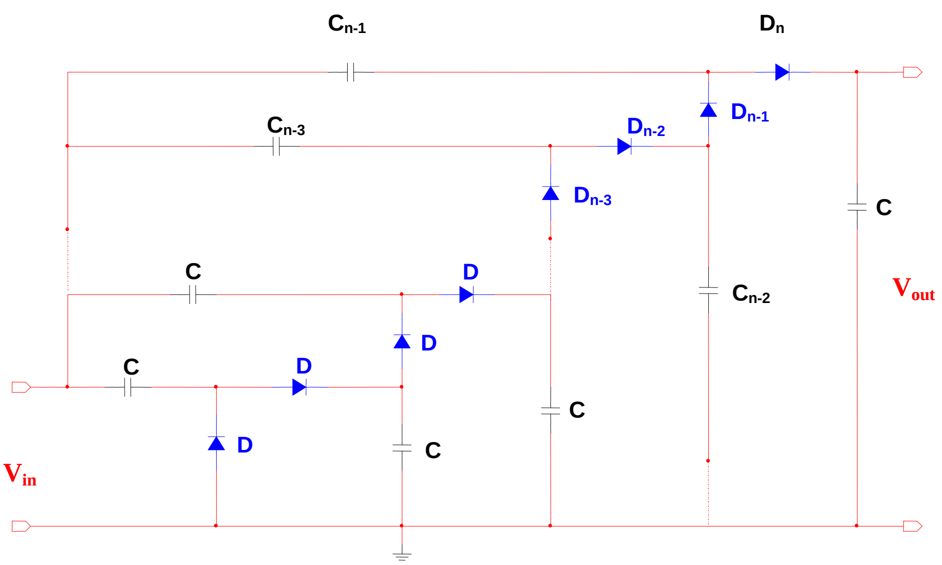

Fig. 3.2: A n-Stage Dickson Voltage Multiplier Circuit

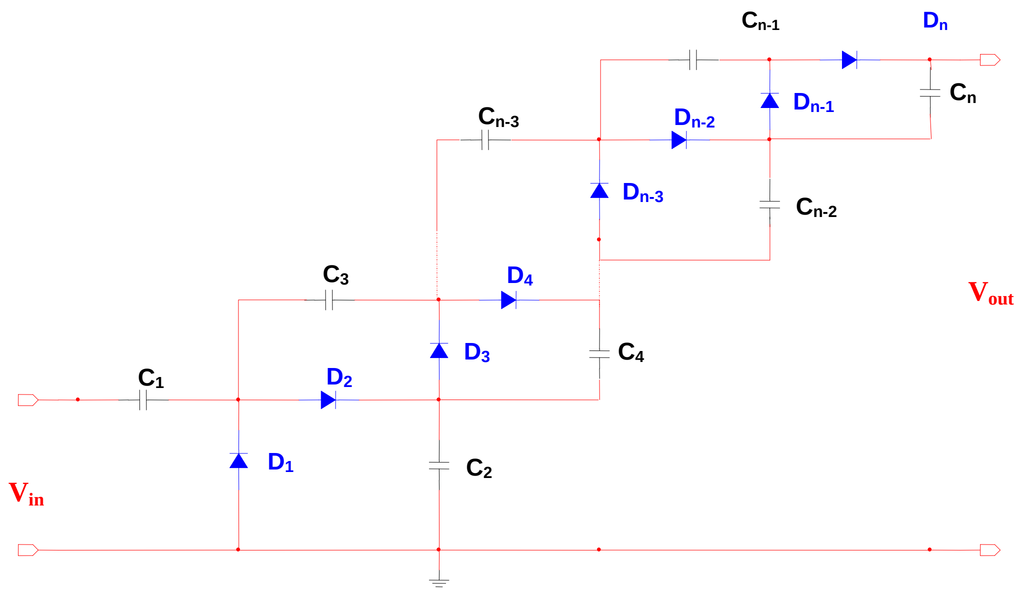

Fig. 3.3: A n-Stage Villard Voltage Multiplier Circuit

The output voltage from the n-Stage Villard and Dickson Voltage doubler Circuit is given by

$$V_{out} = 2n\,(V_{in} - V_{th}) \qquad \text{............ 3.4}$$

Where V_{th} is the forward voltage of the diodes (threshold voltage)and the number of stages is n. But the input voltage for energy harvesting is lower than 200mV which is much smaller than the forward voltage for silicon diode $V_{th} \approx 600$ mV, so that not available solution to generate DC voltage from energy harvesting.

To increase the output voltage, we must be minimized the threshold voltage of the rectifying diodes. Schottky diode offer high switching speed and low forward voltage between 150-450 mV, and it's ideal component for Energy Harvesting, The stage number used in the rectifier has a major effect on the harvesting circuit, but the contrariness of Schottky diodes with CMOS technology makes it not a practical choice for this purpose [7,28].

3.2 Diode-Connected MOSFET Based rectifier and Multiplier circuit

When presenting the diode-connected PMOS transistor as a diode, the transistor will activate when it's in forward biased and it will turn off during the reverse biased, which is similar with a diode. The gate of the diode-connected transistor has been connected to its drain. The bulk or substrate of the NMOS must always connect with the lower voltage terminal, while the PMOS substrate must connect with the highest voltage terminal [10]. The substrate of diode connected PMOS transistor that's connected is as shown in Figure 3.4

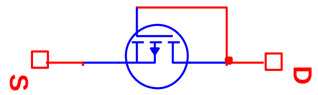

Fig. 3.4: Diode-connected PMOS

In Figure 3.5is shown a one-Stage Dickson and Villard Voltage Multiplier Circuit. $D_1$and D_2 from Figure 3.1 are replaced by Q_1 and Q_2 transistors, and therefore the schematic is redrawn. The multiplication action are often described as follows.

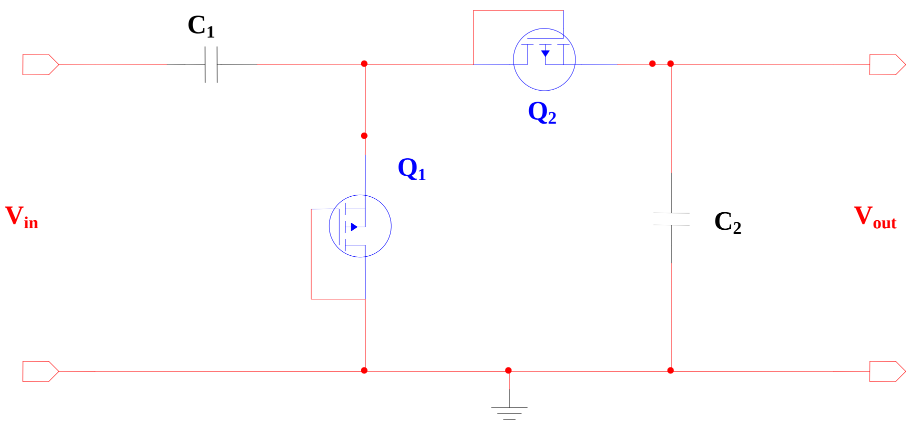

Fig 3.5. A one Stage Dickson and Villard based Diode connected PMOS

Let us assume at the beginning$V_{C1} = 0$, $V_{C2} = 0$, and $C_1 = C_2$,let the amplitude of the input ac voltage be V_{in}, This circuit use to change the AC to high DC signal. When the AC signal is in a negative $(-V_{in})$, the PMOS Q_1 is forward biased and PMOS Q_2 is in reverse biased. The current will flow into C_1 and charge it until the voltage rise to $V_{in} - V_{(gs)th}$ where $V_{(gs)th}$ is voltage between gate and source transistor that's mean threshold voltage is Thus, when an AC signal is in a positive $(+V_{in})$, the PMOS $Q_2$is forward biased and PMOS $Q_1$is in a reverse biased. Then, the current will flow throughC_2 andQ_2. The current throughC_2 is not only derived from the voltage source V_{in}, but also from C_1. Thus, the total voltage generated is twice of the voltage source.

$$V_{C1} = V_{in} - V_{(gs)th} \quad \text{.......... } 3.5$$

$$V_{C2} = V_{C1} + V_{in} - V_{(gs)th} = 2(V_{in} - V_{(gs)th}) \quad \text{.......... } 3.6$$

$$V_{out} = 2(V_{in} - V_{(gs)th)} \quad \text{.......... } 3.7$$

Figure 3.6 shown the n-stage PMOS based Dickson voltage multiplier and Figure 3.7shownthe n-stage PMOS based Villard voltage multiplier.

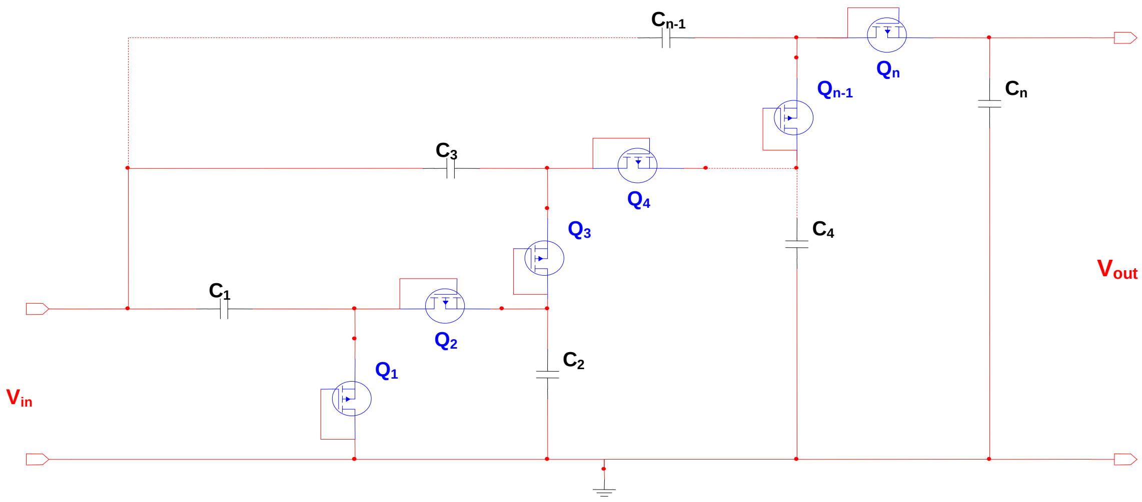

Fig. 3.6: A n-Stage PMOS based Dickson Voltage Multiplier Circuit

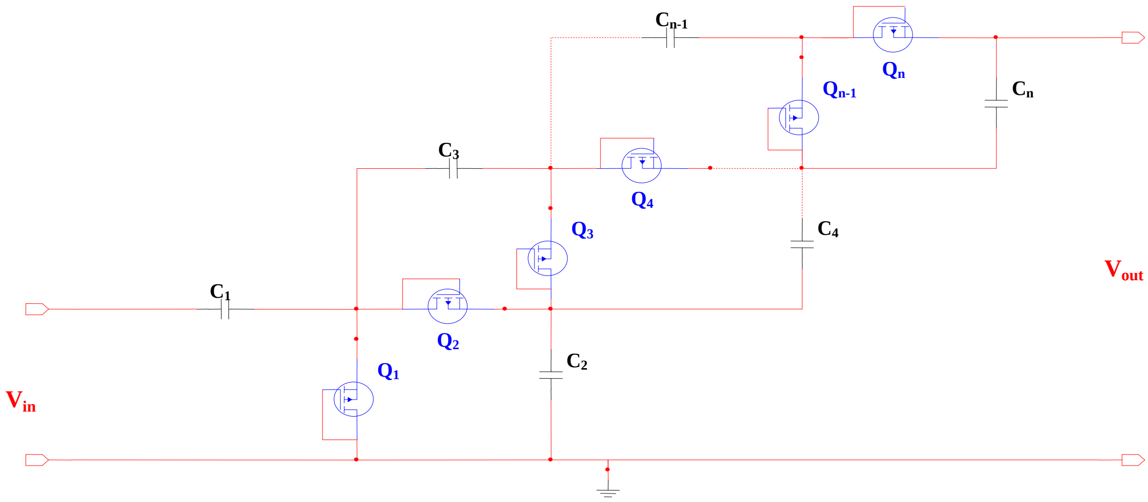

Fig. 3.7: A n-Stage PMOS based Villard Voltage Multiplier Circuit

The output voltage for n-Stage PMOS based Villard and Dickson Voltage Multiplier Circuit is given by.

$$V_{out} = 2n\,(V_{in} - V_{(gs)th}) \qquad \text{............ } 3.8$$

The input voltage for energy harvesting is very low and the threshold voltage for PMOS diode $V_{(gs)th} \approx 300$ mV ,so that not available solution to generate DC voltage from energy harvesting .

3.3 Reverse Current Protection from the storage

Reverse current occurs when the output voltage is more than the input voltage value, so that current flows back through the system, and it damages the rectifier circuit of the system. The first method to solution reveres current by use of a Schottky diode; they need lower threshold voltage, however they're dearer and high reverse current leakage which could cause more problems for the system second method by using dual FET (Back-to-Back) this method high performance but the implementation takes large area on the board and requiring several components to create the system see figure 3.8 and figure 3.9 shown the two method respectively [29].

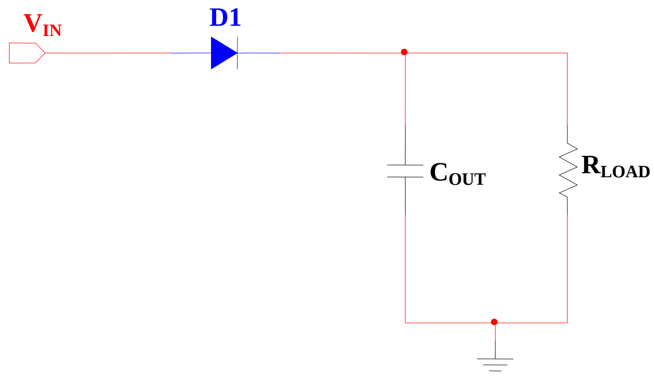

Fig. 3.8. Reverse Current Blocking With a Diode [29]

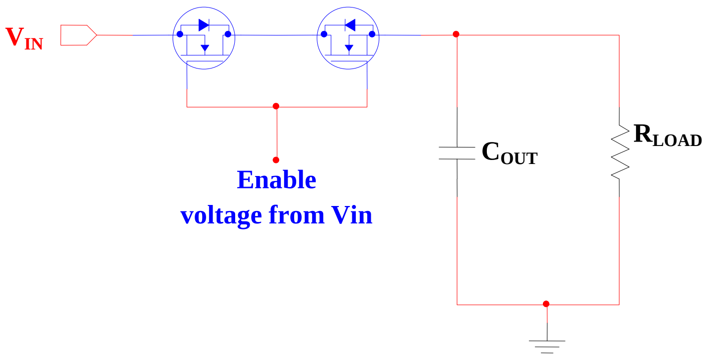

Fig. 3.9. Reverse Current Blocking with Dual FETs [29]

Figure 3.10 shown the Load switches are built-in electronic switches that are accustomed start and stop the facility. Almost like to the dual-FET configuration, the load switches block current in both directions upon shutdown, providing the added benefits of reducing space. Most primary load switches accommodates four pins: input voltage, enable, ground, and output voltage. It includes many features, including reverse current protection, inrush current control, fast output discharge, and programmable rate of flow, in an integrated small package [29].

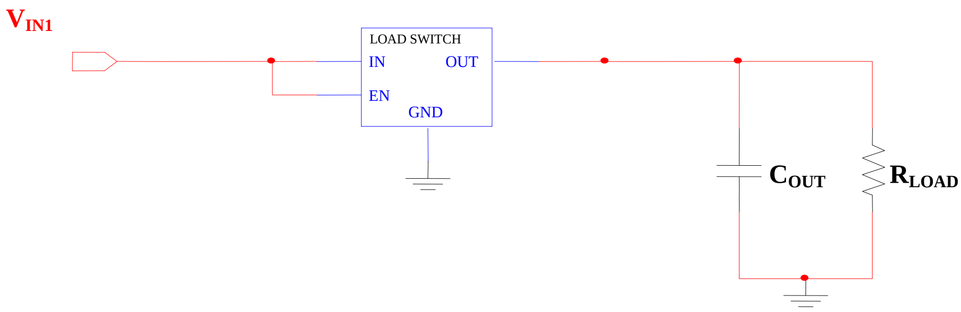

Fig 3.10. Reverse Current Protection with a Load Switch [29]

The threshold voltage V_{th} is the principle supporter of low output voltage, efficiency drop, and power loss. No less significant falling apart factor is reverse leakage current or secondary leakage current.These two parameters need to be should be managed. However, harvesting power in low power threshold requires another structure to restrict and control such components. The establishment of the proposed structure is originating from such establishing and it will be talked about in the Chapter 4.

CHAPTER 4

PROPOSED ENERGY HARVESTING TO DC CONVERTER AND ANALYSIS

To overcome the previously mentioned disadvantages of conventional rectifiers, we developed a new rectifier structure on the basis of the following concepts, to solve the issue of the threshold voltage drop from the diode and diode connected MOSFET, and also the reverse current from the storage system rectifier capacitor should be suppressed as much as possible.

4.1 The Proposed Rectifier Circuit

Starting from the conventional diode-connected MOSFET using NMOS and PMOS, Figure 4.1 shown the Dickson rectifier based diode-connected MOSFET.

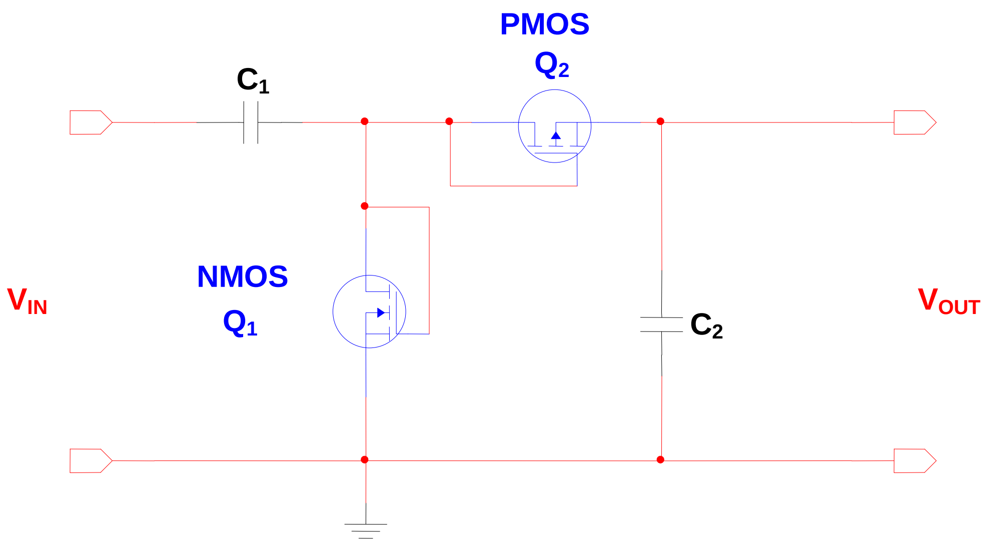

Fig. 4.1. The Dickson rectifier based Diode-connected PMOS and NMOS

If V_{GS1} for Q_1equal V_{GS2} for Q_2 ,the output voltage can be described as :

$$V_{OUT} = 2(V_{IN} - V_{GS}) \qquad \text{.............4.1}$$

Where $V_{IN}$the input voltage from RF or piezoelectric energy harvesting sources, V_{OUT} is the output voltage, and V_{GS} is the voltage between gate and source MOS transistors but when we connect gate with drain ($V_{GS} = V_{TH}$) where V_{TH} is threshold voltages of the PMOS and NMOS transistors. The output voltage when we use n stage Dickson charge pump is given by equation 4.2.

$$V_{OUT} = 2n\ (V_{IN} - V_{(GS)TH}) \qquad \text{.............4.2}$$

Self-threshold voltage cancellation (SVC) shown in Figure 4.2 is used in [27] , in this circuit the threshold voltage is decrease by using the transistor at the same amount of the output DC voltage .

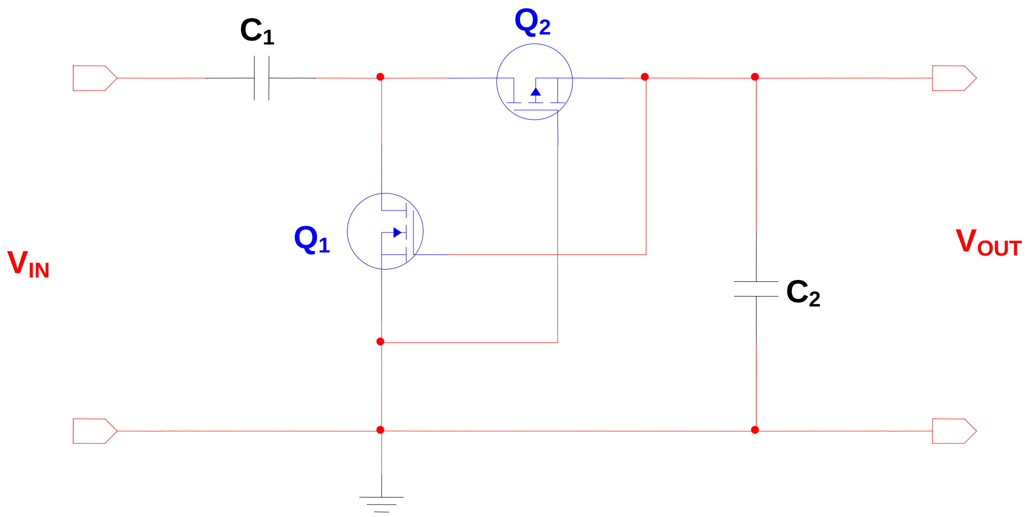

Fig 4.2. The Dickson rectifier based Self-threshold voltage cancellation (SVC)

From figure 4.2 the output voltage is:

$$V_{C1} = V_{IN} + V_{DS1}$$

$$V_{OUT} = V_{DS2} + V_{C1} + V_{IN}$$

$$V_{OUT} = 2V_{IN} + V_{DS1} + V_{DS2} \qquad \text{..............4.3}$$

Where V_{DS1} is the voltage between drain and source CMOS transistors Q_1, V_{DS2} is the voltage between drain and source CMOS transistors Q_2.

If $V_{DS} \leq V_{GS} - V_{TH}$, at this point the device operates in the triode region when the drain current does not follow and if $V_{DS} > V_{GS} - V_{TH}$, I_D becomes relatively constant the transistor saturation region, Figure 4.3 shown the triode region and saturation region [30].

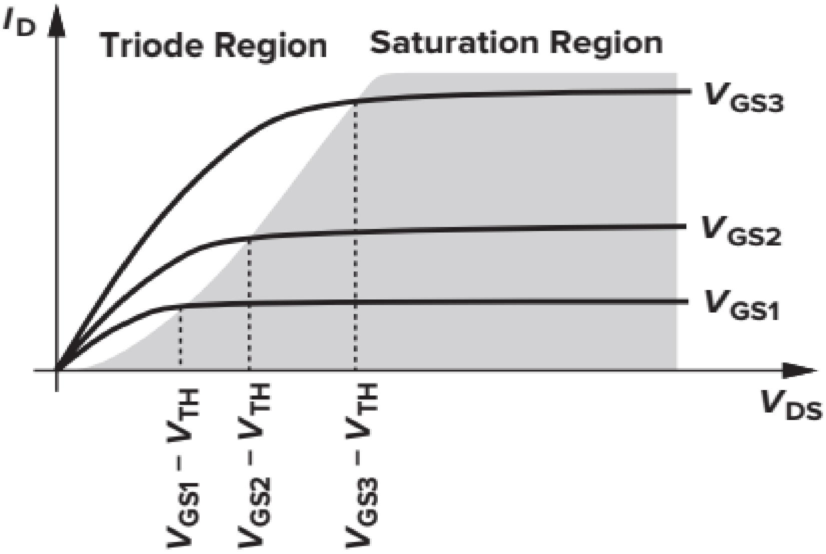

Fig 4.3. The triode region and saturation region of drain current [30]

From the figure 4.3, the reader can show that the pinnacle of every parabola happens at $V_{DS} = V_{GS} - V_{TH}$ and $I_{DS.MAX}$ is the peak current [30]

$$I_{DS.MAX} = \mu_n * C_{ox} * (\frac{W}{L}) \frac{(V_{GS} - V_{TH})^2}{2} \qquad \text{...........4.4}$$

$$\beta = \mu_n * C_{ox} * (\frac{W}{L}) \qquad \text{...........4.5}$$

The linear relationship suggests that the way from the source to the drain can be spoken to by a straight resistor equivalent to [30]

$$R_{on} = \frac{1}{\beta(V_{GS} - V_{TH})} = \frac{1}{\mu_n * C_{ox} * \left(\frac{W}{L}\right) * (V_{GS} - V_{TH})} \qquad \text{............4.6}$$

Where β describing the dependence of I_D upon the constant of the technology, $\mu_n C_{ox}$, the device measurements, W and L, and the gate and drain possibilities regarding the source and R_{on} is on-resistance [30] , in NMOS I_D flows from the drain to the source, whereas holes flow in the reverse direction. Note that V_{GS}, V_{DS},V_{TH}, and $V_{GS} - V_{TH}$ are negative for a PMOS transistor that is turned on .

Set $V_{DS} = V_{GS} - V_{TH}$ in equation 4.3 the output voltage is

$$V_{OUT} = 2V_{IN} + V_{DS1} + V_{DS2}$$

$$V_{OUT} = 2V_{IN} + V_{GS1} - V_{TH1} + V_{GS2} - V_{TH2}$$

The two transistor is the same characteristic then $V_{TH1} = V_{TH2} = V_{TH}$ and from figure 4.2 $V_{GS1} = V_{TH1}$ at the last equation output voltage is

$$V_{OUT} = 2V_{IN} + V_{GS2} - V_{TH} \quad ....4.7$$

From figure 4.2 $V_{GS2} = V_{DS1}$ then V_{OUT} is :

$$V_{OUT} = 2V_{IN} + V_{DS1} - V_{TH}$$

$$V_{OUT} = 2V_{IN} + V_{GS1} - 2V_{TH} \quad ....4.8$$

In this configuration for one stage, the voltage between gate and source is applied to the MOS transistors to reduce the effective V_{TH}. That means the threshold voltage cancelation from the gate-source voltages V_{GS} then the output voltage increase.

Figure 4.4 shown the proposed rectifier circuit, the rectifier circuit at one stage introduce output DC voltage on C_2.This rectifier circuit is designed as a capacitive network instead of resistive network to diminish the static power loss in customary V_{TH} dropping circuit.

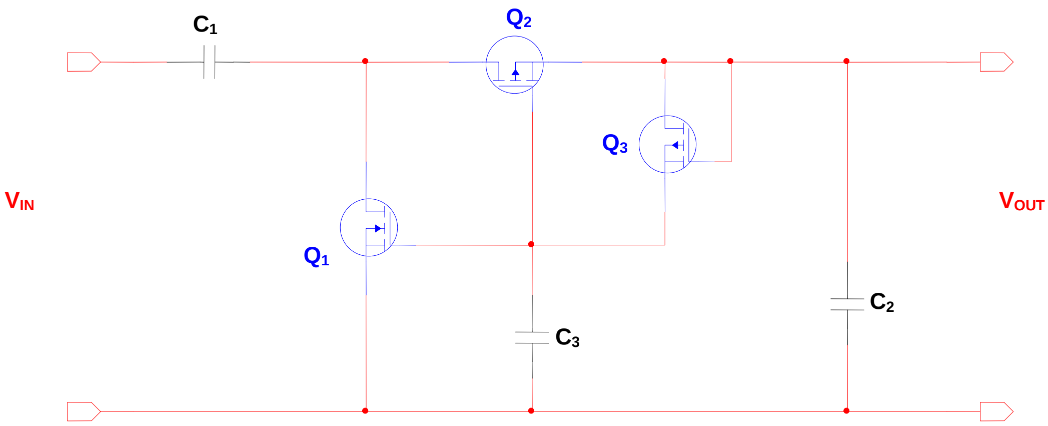

Fig 4.4. The proposed rectifier circuit at one stage

Circuit analysis for the design proposed rectifier circuit, the proposed system contains three transistor MOS , one NMOS $Q_1$and two PMOS Q_2,Q_3 .and the system contains three capacitor C_1, C_2, C_3 From figure 4.4 the output voltage can be analysed in two cycle from the input voltage first at the negative cycle and the second at the positive cycle.

The Q_3 and C_3 network is acting as an automatic switch. At the beginning all transistor MOS in cut-off region, at the negative half cycle Q_1 in cut-off and the leakage current thru Q_1 not effect are, at the positive half cycle in cut-off but the leakage current thru Q_2 pass thru Q_3 and charge capacitor C_3,the voltage capacitor is equal the voltage gate for transistor Q_1 and Q_2 then the transistor Q_2 in triode region and the voltage gate increase until the transistor Q_1 and Q_2 in saturation region, in the negative cycle the current thru Q_1 and charge the capacitor C_1,and in the positive cycle the current thru transistor Q_2 and charge capacitor C_2 and the voltage for capacitor C_2equal the output voltage for one stage rectifier .

At the beginning Let us assume $V_{C1} = 0$, $V_{C2} = 0$, $V_{C3} = 0$ and $C_1 = C_2$,let the amplitude of the input ac voltage be V_{IN}, This circuit serves to change the AC to high DC signal. When the AC voltage is in a negative cycle $(-V_{IN})$ after active tow transistor Q_1 and Q_2 , the NMOS Q_1 is forward-biased and PMOS Q_2 is in reverse-biased. The current will flow into C_1 and charge it until the voltage rise to $V_{IN} + V_{DS1}$ where V_{DS1} is voltage between drain and source transistor that's mean threshold voltage is Thus, when an AC voltage is in a positive cycle $(+V_{IN})$, the PMOS $Q_2$is forward-biased and NMOS $Q_1$is in a reverse-biased. Then, the current will flow through $C_2$and Q_2. The current through C_2 from the voltage source V_{IN}, and (C_1,C_3) Thus, the output voltage is twice of the voltage source.

$$V_{C1} = V_{IN} + V_{DS1} \qquad \text{.......................} \quad 4.9$$

$$V_{C2} = V_{IN} + V_{c1} + V_{DS2}$$

$$V_{C2} = V_{IN} + V_{IN} + V_{DS1} + V_{DS2}$$

$$V_{OUT} = 2V_{IN} + V_{DS1} + V_{DS2} \qquad \text{.......................} \quad 4.10$$

$$V_{OUT} = 2V_{IN} + V_{GS1} - V_{TH1} + V_{GS2} - V_{TH2}$$

From figure 4.4 $V_{GS2} = V_{TH1}$ and if $V_{TH1} = V_{TH2} = V_{TH}$ then V_{OUT} is

$$V_{OUT} = 2V_{IN} + V_{GS1} - V_{TH} \qquad \text{.....................} \quad 4.11$$

Figure 4.5. Shown the n-stage is the proposed circuit based Dickson voltage multiplier and the output voltage is

$$V_{OUT} = 2n\,V_{IN(peak)} + nV_{GS1} - n\,V_{TH} \quad \text{.....................} \quad 4.12$$

From last equation 4.11 for the proposed rectifier circuit at one stage the drop voltage equal V_{TH} and in Self-threshold voltage cancellation (SVC) the drop voltage equal $2V_{TH}$ that means the proposed rectifier circuit more efficiency.

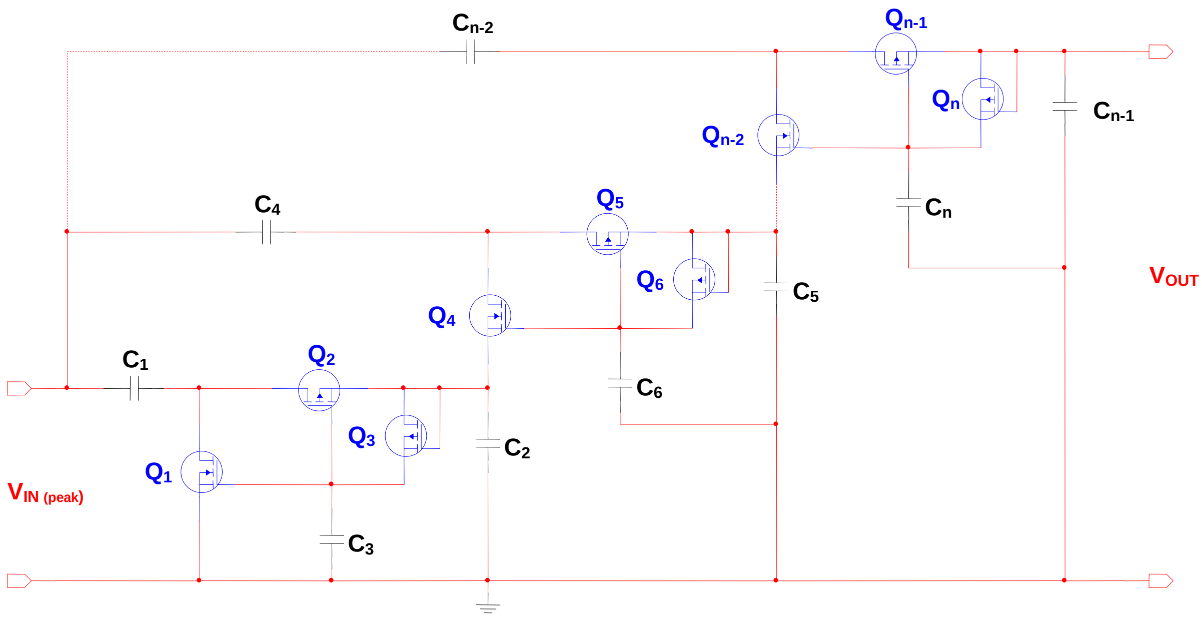

Fig 4.5. The n-stage the proposed circuit based Dickson voltage multiplier

The diode-connected PMOS-NMOS , Self-threshold voltage cancellation (SVC) and the proposed rectifier have been implemented into the three stages Dickson rectifier in 7 nm CMOS Technology, New concepts related to the design of FinFET and design for manufacturing [31]. The design parameter of these three topologies was set as shown Table 4.1.

Table 4.1 key parameters of the 7-nm CMOS Technology

Parameter	**Code**	**7-nm process**	**Unit**
The Effective Length	L	7	nm
The Effective Width	W	42.5	nm
Fin Height	H_{fin}	18	nm
Fin Width	W_{fin}	6.5	nm
Gate-Oxide Thickness	T_{ox}	1.15	nm
Core Supply	V_{DD}	700	mV
Threshold Voltage	V_{TH}	62.4	mV

From equation 4.6 we can find R_{on} on-resistance where $\mu_n * C_{ox} = 0.81\ mA/V^2$ and $\left(\frac{W}{L}\right) = \left(\frac{42.5}{7}\right)$ from the table 4.1 can be represented by this equation :

$$R_{on} = \frac{1}{\mu_n * C_{ox} * \left(\frac{W}{L}\right) * V_{DS}} = \frac{1}{0.81 * 10^{-3} * \left(\frac{42.5}{7}\right) * V_{DS}} \qquad ....4.13$$

Figure 4.6 shown the relationship between the voltage V_{DS} and R_{on}.

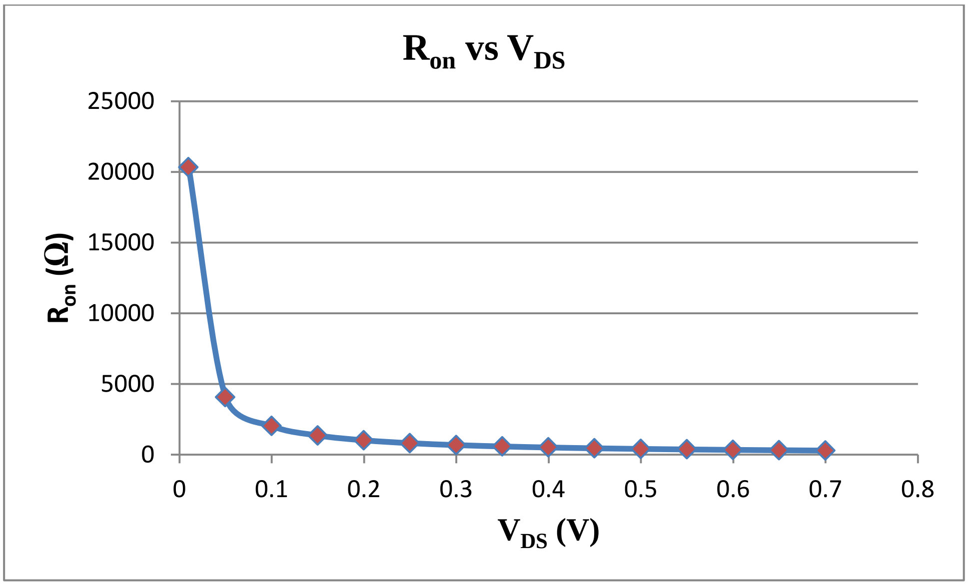

Fig 4.6. The R_{on} on-resistance of CMOS transistor as a function of V_{DS}

From equation 4.4 we can find I_D where $\mu_n * C_{ox} = 0.81\ mA/V^2$ and $\left(\frac{W}{L}\right) = (\frac{42.5}{7})$ from the table 4.1 can be represented by

$$I_{DS.MAX} = \mu_n * C_{ox} * \left(\frac{W}{L}\right)\frac{(V_{DS})^2}{2} = 0.81 * 10^{-3} * \left(\frac{42.5}{7}\right) * \frac{V_{DS}^2}{2} \quad ....4.14$$

Figure 4.7 shown the relationship between the voltage V_{DS} and I_{DS}.

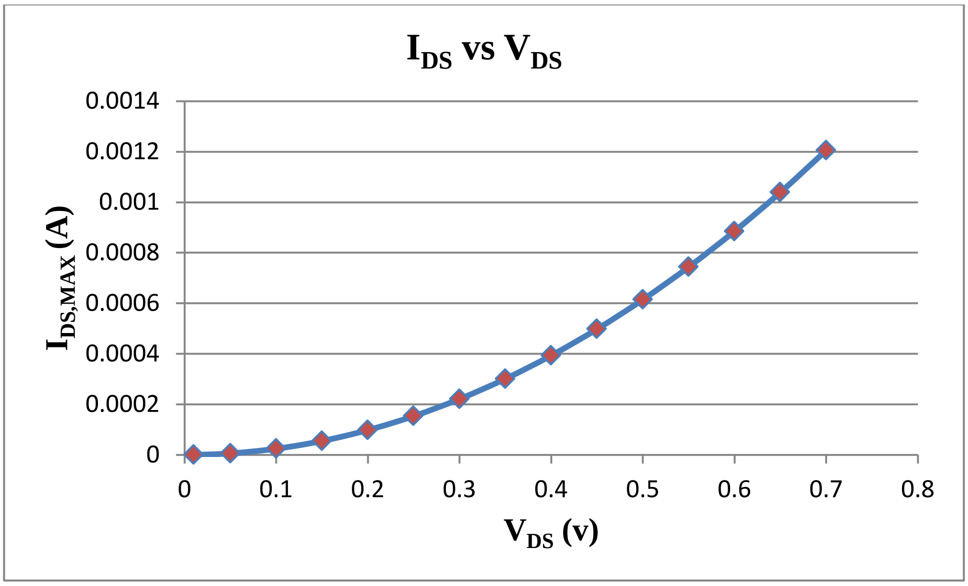

Fig 4.7. The peak current $I_{DS,\ MAX}$ of CMOS transistor as a function of V_{DS}

4.1.1 The Proposed Rectifier Circuit for RF energy harvesting

Ambient RF energy typically covers transmission frequency in the range 20kHz – 300 GHz, If the frequency equal 20 kHz and from figure 4.6 we not the on-resistance R_{on}decrease when increase V_{DS} if V_{DS} = 2 V then R_{on} = 100 Ω , the capacitance for the proposed rectifier circuit is where F is the frequency [30]

$$C_n = \frac{1}{R_{on}F} \quad ....4.15$$

From equation 4.14 the capacitance C_n = 0.5uF, the proposed rectifier circuit at 12-stage shown in figure 4.8 at the input voltage from the radio frequency RF energy harvest is 150 mV_{peak} , and from figure 4.9 the output voltage reach saturation at t= 0.25 ms ,V_{OUT} = 4.8 V this value can be charge any small application .

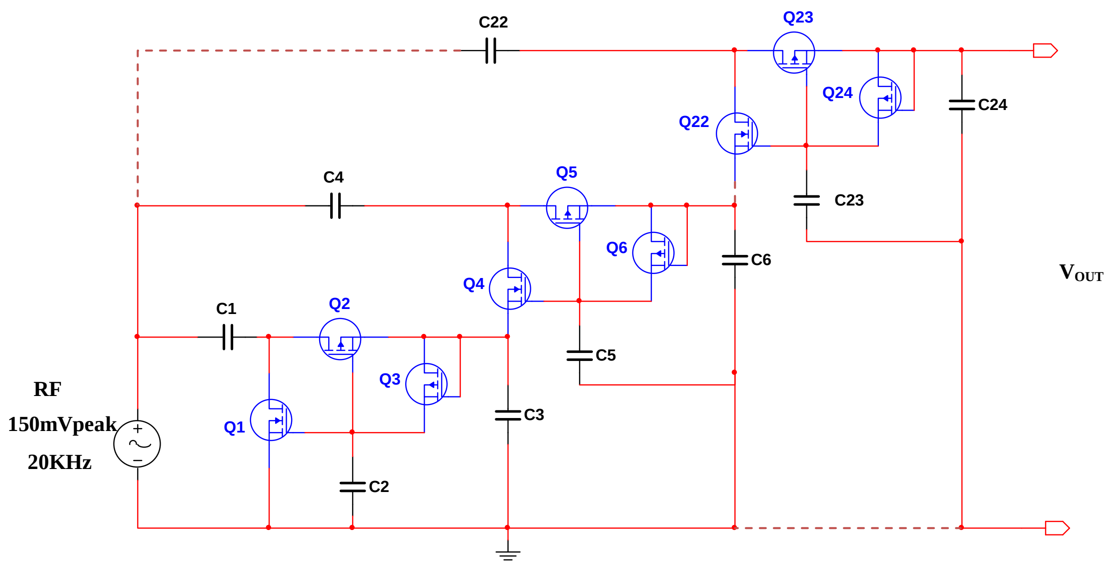

Fig 4.8. The proposed rectifier circuit at 12- stage when input voltage from RF

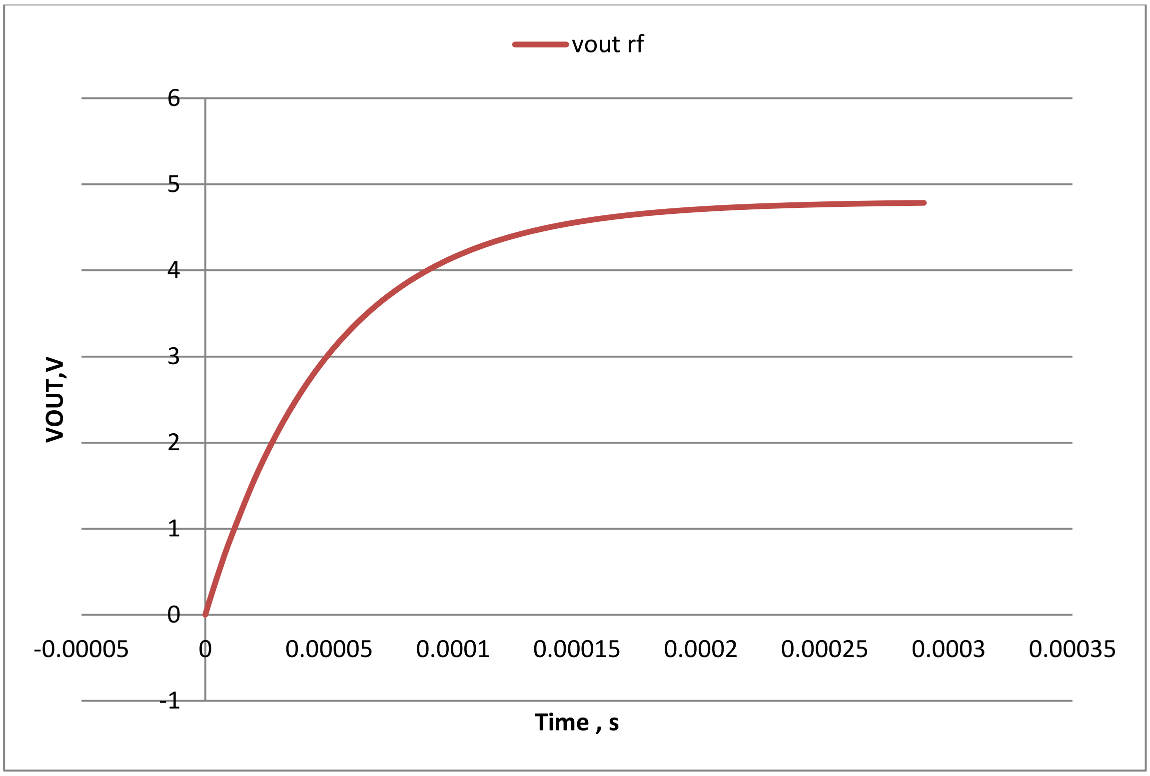

Fig 4.9.The output voltage for proposed rectifier circuit at 12-stage at V_{IN} =150 mV from RF

4.1.2 The Proposed Rectifier Circuit for piezoelectric energy harvesting

The frequencies of a portion of the common vibration sources are recorded in Table 4.2. Most hardware gear has a frequency of 100 Hz or higher, while human or creature movement shows a much lower recurrence, commonly inside the 1–30 Hz range [18].

Table 4.2 Frequency of various vibration sources [18].

Vibration source	Frequency (Hz)
Car instrument panel	13
kitchen blender	121
Clothe dryer	121
HVAC vents in office building	60
Car engine compartment	200
Refrigerator	240
Human walking	2–3

If the frequency equal 100 Hz and from figure 4.6 we not the on-resistance R_{on}decrease when increase V_{DS} if V_{DS} = 2 V then R_{on} = 100 Ω, the capacitance for the proposed rectifier circuit from equation 4.15, the capacitance C_n = 100 uF, the proposed rectifier circuit at 5-stage shown in figure 4.10 at the input voltage from the piezoelectric is 0.5 V_{peak}. and from figure 4.11 the output voltage reach saturation at t= 0.05 s ,V_{OUT} = 5 V this value can be charge any small application .

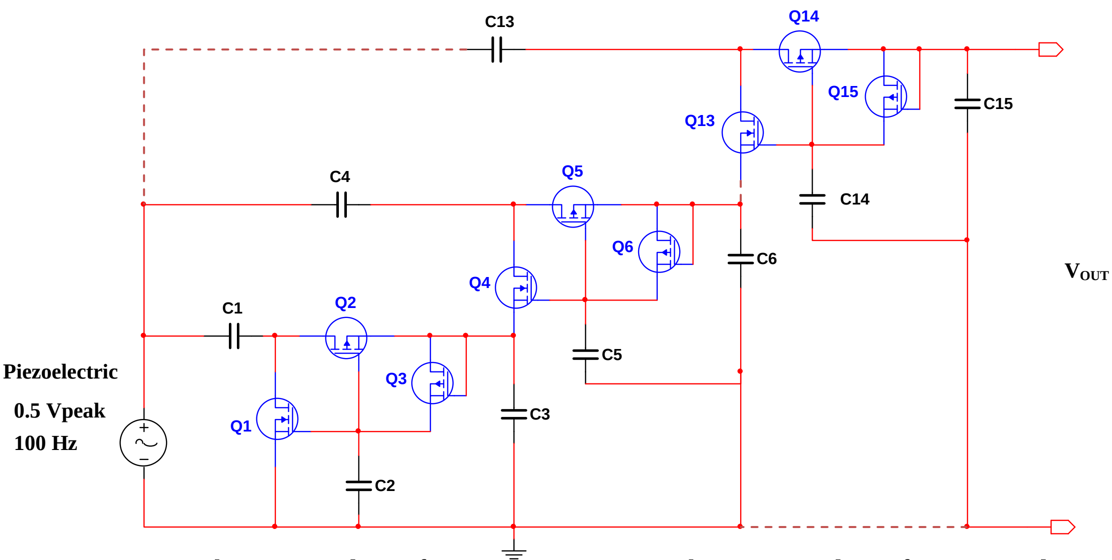

Fig 4.10. The proposed rectifier circuit at 5-stage when input voltage from piezoelectric

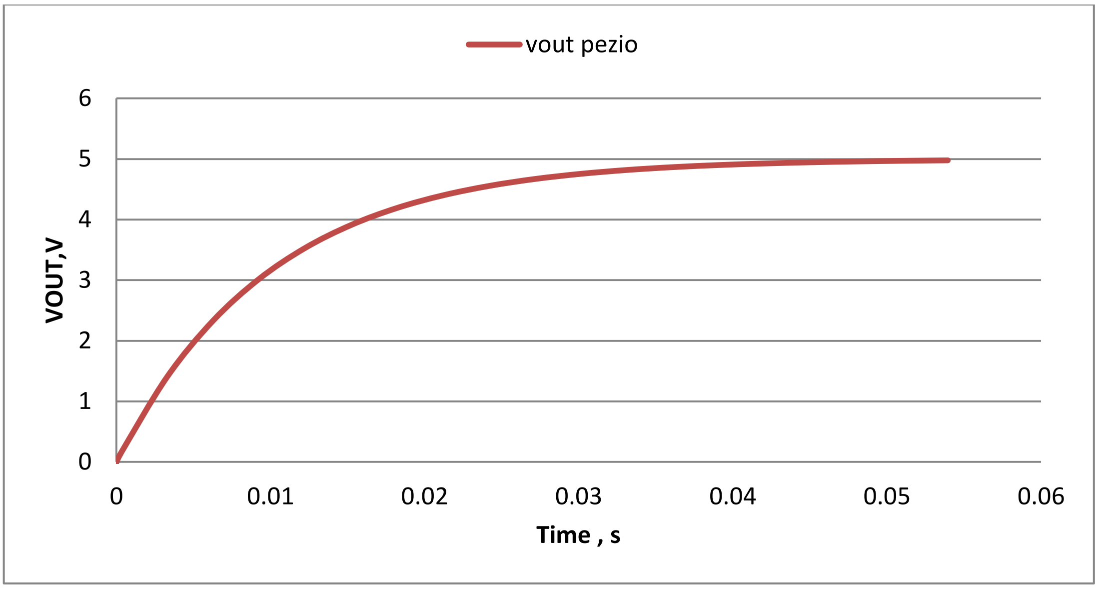

Fig 4.11.The output voltage for proposed rectifier circuit at 5-stage at V_{IN} =0.5 V from RF

4.2 The system design for hybrid energy harvesting

Finally, the hybrid energy harvesting is compile the energy harvesting from two sources RF and piezoelectric, so we needed the electrical circuit to provide voltage from multi source energy and to protection from the reverse current from the storage so we can used load switches are integrated electronic. The TPS22963C is a load switch with invert current hindering. This reverse current impeding feature is possibly initiated when the load switch is turned off see figure 4.12.

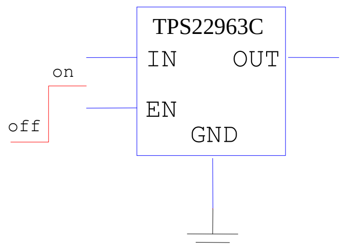

Fig 4.12. TPS22963C Load Switch

Today many application use power supply voltage 3.5 to 5 V DC, so we can use voltage regulator TPS22963C has 5V on the output at active input voltage V_{IN} but when the output voltage not powered the system is unable and protection the system from reverse current, and we can use multi source energy to provide the system and the enable regulator voltage from the input voltage see figure 4.13.

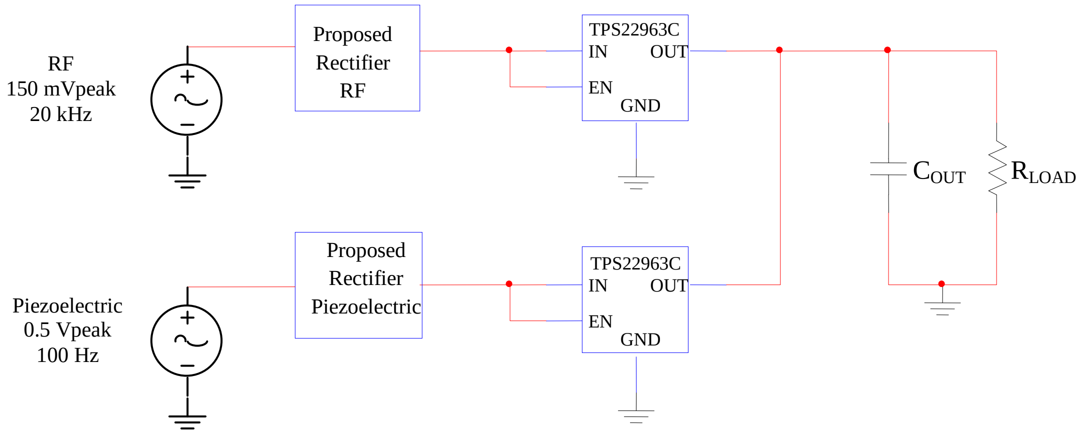

Fig 4.13. Power Mixing using two TPS22963C Load Switch

From figure 4.13 can be provide and regulate the DC voltage from two source energy harvesting RF and piezoelectric, if any source dose not found the load switch not to enable and the load switch protection the rectifier circuit from reverse current. And can be provide the system from two sources at the seam time.

The hybrid energy harvesting system can apply in mobile the radio frequency from the receive signal or transmit and the vibration (piezoelectric) by using touch or socket for the same mobile and then can charge battery.

CHAPTER 5

SIMULATION AND ANALYSIS RESULTS

In this chapter, we will discuss the previous results and work on analysing the results.From figure 4.4 shown the proposed rectifier circuit at one stage and the output voltage from the rectifier circuit, when the input voltage is 0.3 V at frequency is 20 kHz , and from the equation 4.12 show the output voltage at n-stage ,figure 5.1 show the output voltage at 1-stage ,2-stage and 3-stage .

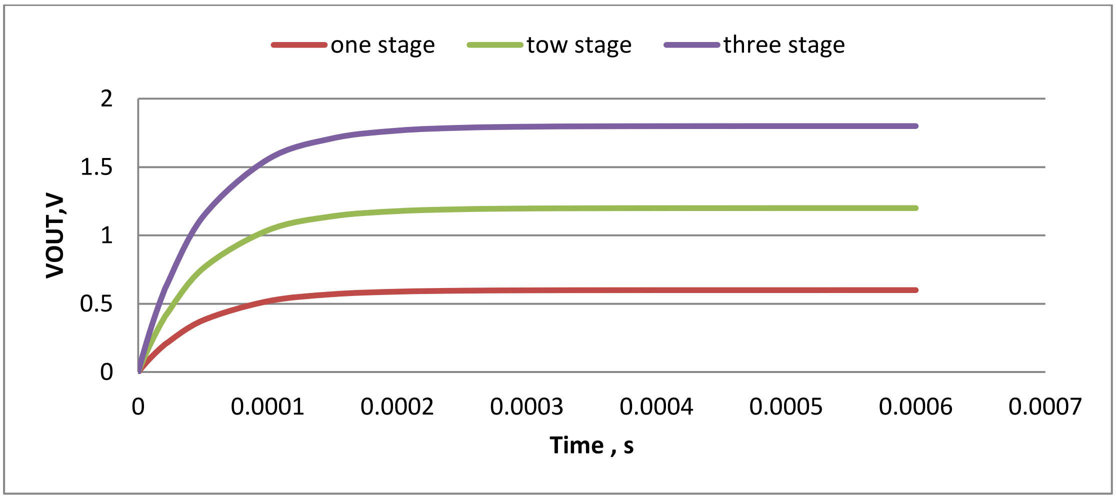

Fig.5.1 The output voltage for proposed rectifier circuit at one stage, two stage and three stage.

From figure 5.1 at t = 21 us the output voltage for each stage respectively is $V_{OUT\ at\ n=1}$= 0.559 V, $V_{OUT\ at\ n=2}$= 1.126 V and $V_{OUT\ at\ n=3}$= 1.689 V.

Figure 5.2 show the output voltage at n=3 in proposed rectifier circuit , rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC) at the input voltage is 0.3 V ,F=20kHz from the figure at t = 0.75 ms the output voltage for each rectifier is $V_{OUT,PROPOSED}$ = 1.8 V ,$V_{OUT,DIODE\text{-}CONNECTED}$= 1.4 V and $V_{OUT,SVC}$ = 1.6 V.

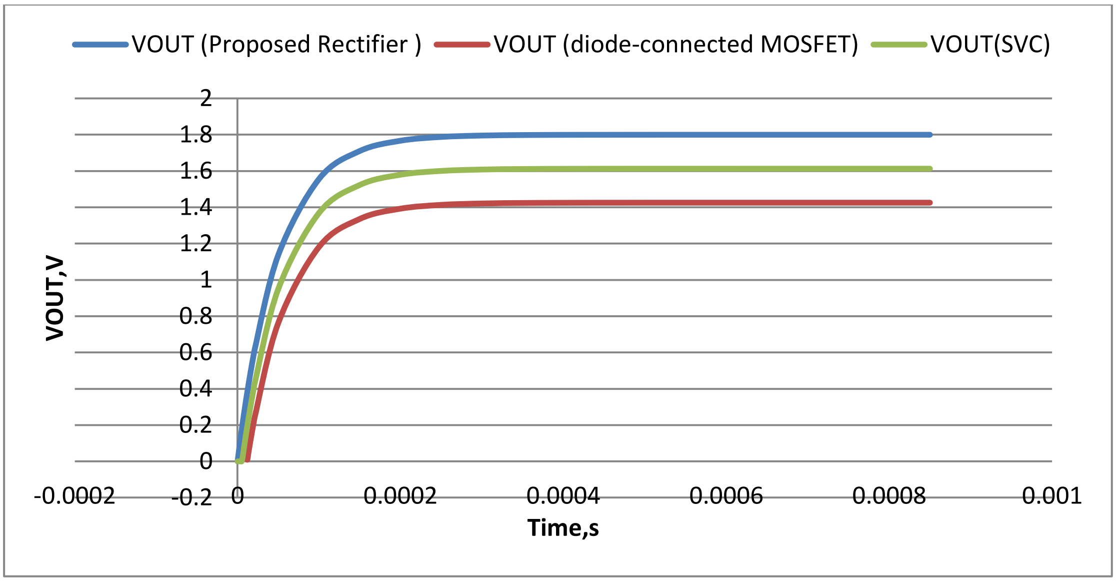

Fig. 5.2 the output voltage at n=3 in proposed rectifier circuit, rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC)

The power conversion efficiency PCE expressed as [32,33] :

$$PCE\% = \frac{P_{out}}{P_{out}+n*P_{loss}}*100\% \qquad \text{.................5.1}$$

$$P_{loss} = P_{FWB} + P_{Rev} \qquad \text{. ....5.2}$$

Where P_{out} is the power delivered to the load, P_{loss} is the total lost power, P_{FWD} is the lost power due to the channel resistance R_{on}, and P_{Rev} is the power loss due to the sub-threshold leakage current; n is the number of stages. Figure 5.3 show the power conversion efficiency PCE at n=3 in proposed rectifier circuit, rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC) at the input voltage is 0.3 V, F=100 kHz from the figure at t = 1 ms the power conversion efficiency is $PCE_{PROPOSED}$ = 43 %, $PCE_{DIODE\text{-}CONNECTED}$= 30% and PCE_{SVC} = 37%.

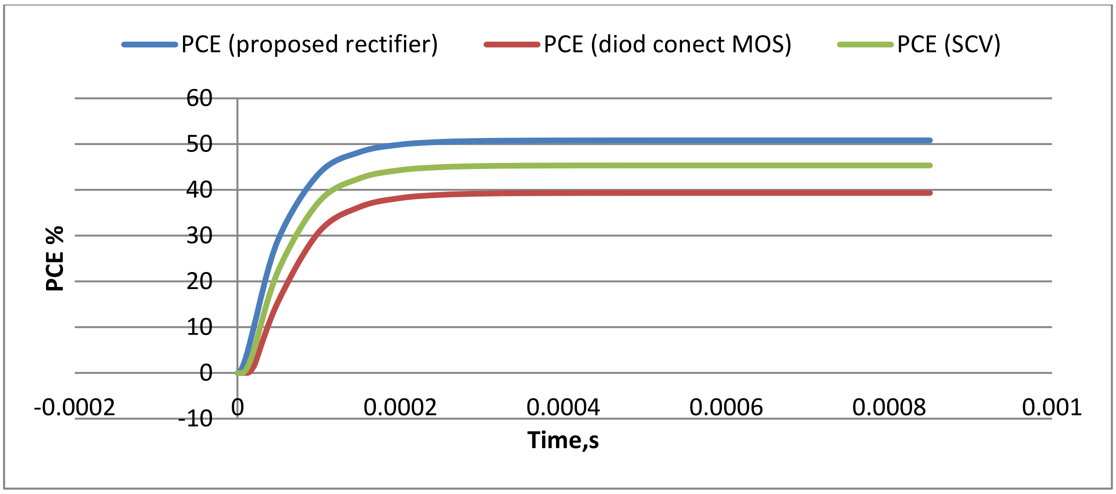

Fig. 5.3 PCE at n=3 in proposed rectifier circuit, rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC)

The calculated voltage conversion efficiency as a function of the input voltage .For this calculation, the rectifier voltage conversion efficiency (VCE) is defined as[34,35]

$$VCE = \frac{V_{OUT}}{V_{IN}} \qquad \text{................5.3}$$

Figure 5.4 show the voltage conversion efficiency VCE at n=3 in proposed rectifier circuit, rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC) at the input voltage is 0.3 V, F=20 kHz from the figure at t = 1 ms the voltage conversion efficiency for each rectifier is $VCE_{PROPOSED} = 5.18$, $VCE_{DIODE\text{-}CONNECTED} = 3.93$ and $VCE_{SVC} = 4.56$.

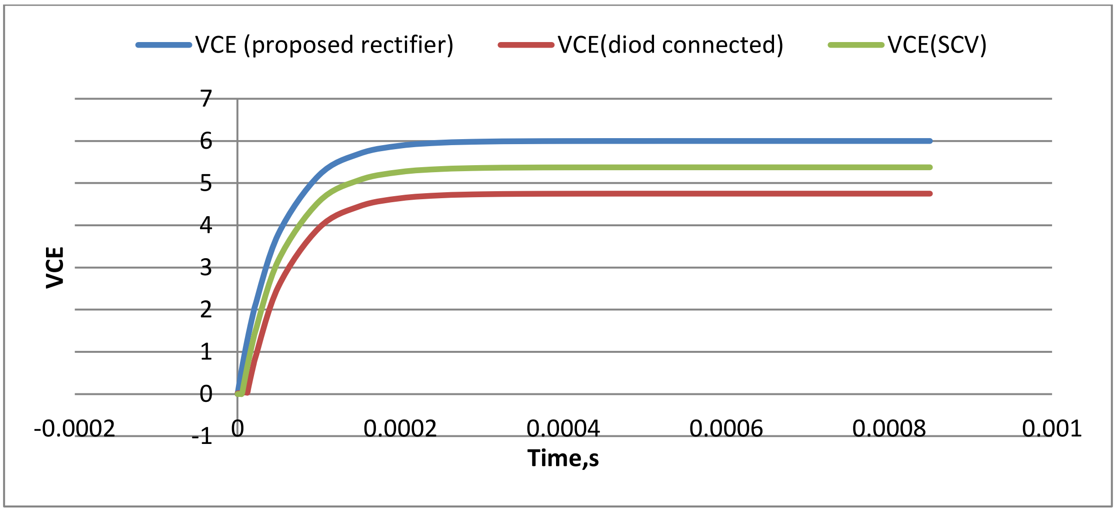

Fig. 5.4 VCE at n=3 in proposed rectifier circuit, rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC)

From the last result the PCE and VCE the proposed circuit rectifier is higher than, rectifier based Diode-connected MOSFET and rectifier based Self-threshold voltage cancellation (SVC).

Figure 5.5 show the PCE at n=3 for proposed rectifier circuit when we change the resistance load R_{load}, at the input voltage is 0.3 V, F=20 kHz from the figure at R_{load}= 100 Ω the PCE is $PCE_{PROPOSED}$ = 41.7%.

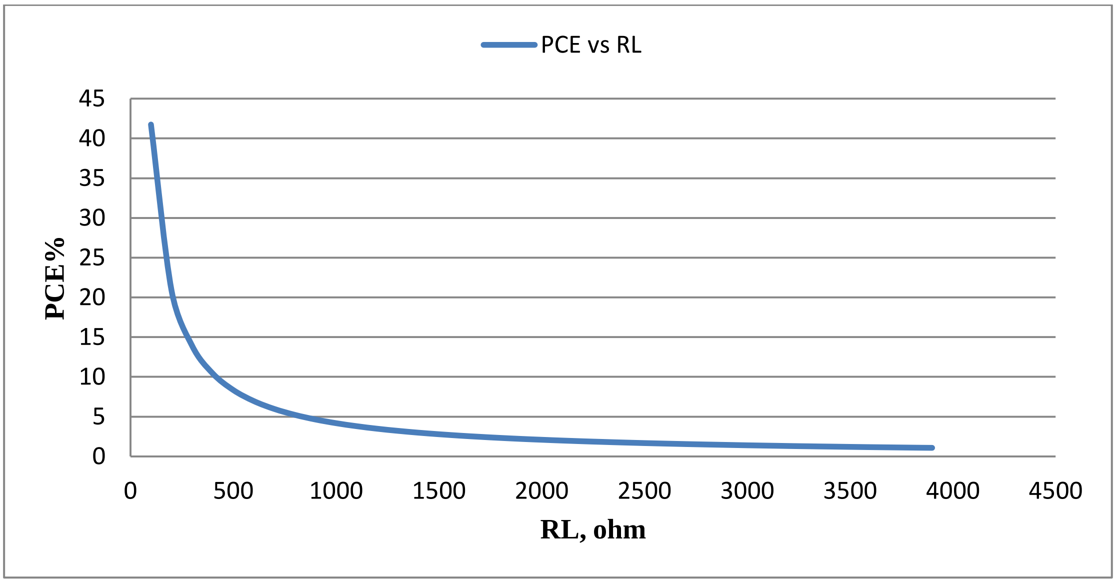

Figure 5.5 the PCE at n=3 for proposed rectifier circuit VS frequency

Figure 5.6 show the PCE at n=3 for proposed rectifier circuit when we change the frequency from the source input, at the input voltage is 0.3 V, from the figure at F = 100 MHz the PCE is $PCE_{PROPOSED}$ = 41.7%.

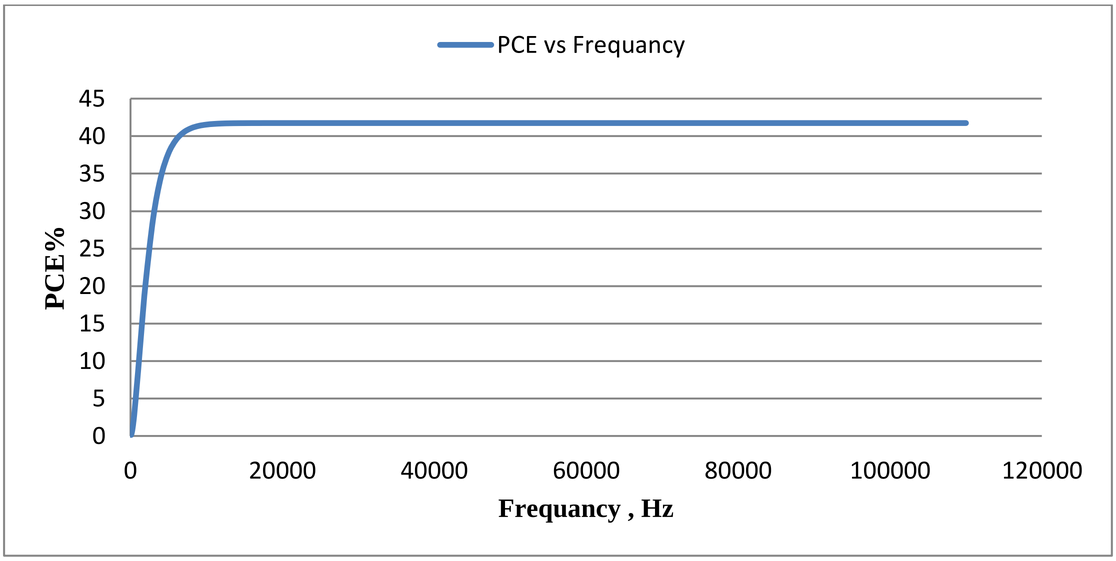

Figure 5.6 the PCE at n=3 for proposed rectifier circuit VS frequency

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

- Although many studies touched on energy harvesting and how to convert energy from type to type by using many rectifier circuit sample.
- In this thesis we analyse these circuit and we find some problem we worked to improve this system by using a proposed rectifier circuit that give us a higher efficiency compared to aforementioned circuit and we could overcame the threshold voltage drop.
- Those two points were an obstacle in the path of researchers previously, we solve those problems, and then we can collect energy from many sources to power any smart system.

6.2 Future Work

Based on the results that have been reached:

1. We increased efficiency of rectifier circuit to 50 % compared to the efficiency reached by researchers previously.
2. The voltage reaches stability in a brief period of time, which is estimated to be nanoseconds

We can develop the following solutions**:**

1. Designing an integrated system for collecting and storing energy with high efficiency and with a very small input voltage
2. Using output energy in smart applications as charging mobile.
3. Reducing the size of the circuit as large as possible for use in medical applications such as the heart battery, where we used 7-nm technology which is very small compared to previously used technologies.

References

[1]. N. Kumar, et al. (2018). "RF Energy Harvesting and Storage System of Rectenna: A Review." Indian Journal of Science and Technology 11(25): 1-5.

[2]. El-Sayed I. E. Shalaan.(2018). Design and Development of Energy Harvesting Devices for Wireless Power Transmission. Saudi Arabia: King Abdulaziz University.

[3]. C. A. Gould and N. Shammas, (2009). “A review of thermoelectric MEMS devices for micropower generation, Micro Electronic and Mechanical Systems,” Rijeka, Croatia: InTech Open Access Publisher.

[4]. M.E. Kiziroglou, E.M. Yeatman. (2012). Functional Materials for Sustainable Energy Applications.

[5]. Bouchouicha, D., et al. (2010). Ambient RF Energy Harvesting. Renewable Energy and Power Quality Journal. 1: 1309-1313.

[6]. Z. W. Sim, (2011).Radio Frequency Energy Harvesting for Embedded Sensor Networks in the Natural Environment. thesis. The University of Manchester: School of Electrical and Electronic Engineering.

[7]. M. M. Bait-Suwailam, Z. Nadir . (2014). An Enhanced RF Energy Harvesting System for Low-Power Wireless Sensors in 900 MHz Band. Vol 8.

[8].P. Nintanavongsa., et al.(2012) . Design Optimization and Implementation for RF Energy Harvesting Circuits. IEEE Journal On Emerging And Selected Topics In Circuits And Systems, Vol. 2, No. 1.

[9]. A. Chawanda., et al.(2017). Radio Frequency Energy Harvesting Sources. Acta Electrotechnica et Informatica, Vol. 17, No. 4, 19–27.

[10]. Y.C. Wong, et al. (2016). Dickson Charge Pump Rectifier using Ultra-Low Power (ULP) Diode for BAN Applications. Technical University of Malaysia Malacca.

[11]. H. Jabbar., et al.(2010). RF Energy Harvesting System and Circuits for Charging of Mobile Devices. IEEE.

[12]. Anitha Govind. Antenna Impedance Matching – Simplified. Abracon LLC

[13].W.Wang.(2017) . Gated Self-Matching Networks for Reading Comprehension and Question Answering. Vancouver, Canada :Annual Meeting of the Association for Computational Linguistics, Pp 189–198.

[14]. I. Chaour , A. Fakhfakh and O. Kanoun (2017). Enhanced Passive RF-DC Converter Circuit Efficiency for Low RF Energy Harvesting. Sensors

[15]. D. Harrist. (2001). Wireless Battery Charging System Using Radio Frequency Energy Harvesting. MS Thesis. BS, University of Pittsburgh.

[16].A. M. Zungeru, . Ang, SRS. Prabaharan, K. P. Seng.(2018).Radio Frequency Energy Harvesting and Management for Wireless Sensor Networks.Department of Electrical and Electronics Engineering: The University of Nottingham.

[17]. M. Rastmanesh, (2013). High Efficiency RF To Dc Converter With Reduced Leakage Current For RFID Applications. MS Thesis. Dalhousie University Halifax, Nova Scotia.

[18]. Li, H., et al. (2014). "Energy harvesting from low frequency applications using piezoelectric materials." Applied Physics Reviews 1(4): 041301.

[19].A.Takezawa, et al.(2012).Design methodology of piezoelectric energy harvesting skin using topology optimization. Department of Mechatronics and Mechanical Systems Engineering ,Escola Polit´ecnica da Universidade de S~ao Paulo.

[20]. K. Uchino, (2018). "Piezoelectric Energy Harvesting Systems-Essentials to Successful Developments." Energy Technology 6(5): 829-848.

[21]. C. Howells, (2009). "Piezoelectric energy harvesting." Energy Conversion and Management 50(7): 1847-1850.

[22]. M. Yamuna , S. Sundar, et al (2014). Design of Piezoelectric Energy Harvesting and Storage Devices. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineerin, (An ISO 3297: 2007 Certified Organization).

[23]. W. Gharieb, G. Nagib.(2012). Design considerations for piezoelectric energy harvesting systems. IEEE

[24]. K. Naveen , (2015). "Energy collection via Piezoelectricity." Journal of Physics: Conference Series .

[25]. D. Patel1., et al.(2014). RF Energy Harvesting. International Journal of Engineering Trends and Technology (IJETT), Vol 16, No 8.

[26]. S. Agrawal, et al. (2017). "A dual-band RF energy harvesting circuit using 4th order dual-band matching network." Cogent Engineering 4(1): 1332705.

[27]. M. Al-Absi .(2020). Hybrid Internal Vth Cancellation Rectifiers for RF Energy Harvesting. Department of Electrical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

[28]. B. Clerckx, et al. (2015). "Waveform optimization for Wireless Power Transfer with nonlinear energy harvester modeling." 276-280.

[29]. Z. Stokes ; A. Kaknevicius. (2016). Reverse Current Protection in Load Switches.Texas Instruments Incorporated

[30]. B. Razavi. (2017). Design of Analog CMOS Integrated Circuits. 2^ed Ed. University of California, Los Angeles.pp7-30.

[31]. M. Sohaib; T. Mottaqiallah; H. Said. (2019). System-level sub-20 nm planar and FinFET CMOS delay modelling for supply and threshold voltage scaling under process variation. Journal of Low Power Electronics.

[32]. J. Yi; W. Ki; C. Tsui; (2007) Analysis and Design Strategy of UHF Micro-Power CMOS Rectifiers for Micro-Sensor and RFID Applications. IEEE Transactions On Circuits And Systems, Regular Papers, Vol. 54, No. 1.

[33]. K. Kotani, T. Ito; (2009) Self-Vth-cancellation high-efficiency CMOS rectifier circuit for UHF RFIDs. IEICE Trans. Electron., vol. E92-C, no. 1, pp. 153–160.

[34]. N. Tasneem, et al. (2018). "A low-power CMOS voltage boosting rectifier for wireless power transfer applications." 1-4.

[35]. L. Fang, et al. (2018). "The Design of Operational Amplifier for Low Voltage and Low Current Sound Energy Harvesting System." IOP Conference Series: Materials Science and Engineering 318: 012035.