



**CMOS CAPACITANCE SENSING DEVICE AND  
ENERGY HARVESTING FOR WIRELESS SENSING  
SYSTEM USING HYBRID APPROACH**

**BY**

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## ABSTRACT

Sensor measurement using capacitive sensor has gain popularity in many applications over other resistive sensor and inductive sensor. The method of converting stimuli input to a readable detection output voltage can be divided into many broad methods, such as capacitive-to-digital converter (CDC), capacitive-to-frequency converter (CFC) and capacitive-to-voltage converter (CVC). One of the methods in CVC is known as differential CVC. It is known to be a very symmetrical in design, sensitive to detection, accurate and easy to be implemented using discrete components. Previous research to date has shown the range of frequency operation using discrete component is only up to 10 kHz, very low detection range and has only implemented the differential CVC circuit solely using normal power supply or battery dependent. Hence, the objective of this work is to design and evaluate the performance of the differential capacitive sensing, while integrating multiple sources from different harvesters as its power source. Electrical characterization of the device performance is also studied in this research. The proposed differential CVC circuit requires only one single supply from the energy harvester implemented by using hybrid technique and was realised by the discrete components. Results has shown a wide detection range of 2 – 23 pF, and the best is recorded at 200 kHz frequency, with output voltage of 1.5 – 2.22 V. This is realised by implementing 3.3 V power supply, with nominal detection capacitor  $C_{x0} = 5$  pF. Circuit has consumed 3.83 mW of power, which is 28.9 % improvement from the previous result. Both with and without parasitic, the proposed circuit has shown high level of linearity of R-squared value of up to 0.99944 using 0.1 pF capacitance change with sensitivity of 0.05431 mV per fF change, across 40 kHz to 400 kHz frequency. Sensitivity has been improved by 43 % from the previous work. Comparison of the experiment work with the theory has shown 5% error in difference. The proposed differential CVC is also suitable to be used as a sensor node in area that limit access to human for battery replacement and it is suitable to integrate pressure and accelerometer sensor to the system.

## خلاصة البحث

قياس الاستشعار باستخدام جهاز الاستشعار بالسعة كسب شعبية في العديد من التطبيقات مقارنة بجهاز الاستشعار المقاوم وغيره من أجهزة الاستشعار الحثي. ويمكن تقسيم طريقة تحويل مدخلات المحفزات لجهد ناتج بقراءة قابلة للكشف إلى العديد من الطرق الموسعة، مثل محول السعة إلى الرقمية (CDC)، ومحول السعة إلى التردد (CFC) ومحول السعة إلى الجهد (CVC). وإحدى طرق محول CVC تعرف بالمحول التفاضلي للسعة إلى الجهد (CVC التفاضلي) والمعروف بأنه متناظر في التصميم، وحساسية في الكشف ودقة وسهولة في التنفيذ باستخدام مكونات منفصلة. وقد أظهرت الأبحاث السابقة أن مدى تردد العملية باستخدام عناصر منفصلة حتى الآن لم يتجاوز 10 كيلو هرتز، ومدى كشف منخفض جداً كما أن دائرة المحول التفاضلي للسعة إلى الجهد (CVC التفاضلي) تم تنفيذه فقط باستخدام تيار كهربائي عادي أو بالاعتماد على البطارية. الهدف من هذا البحث هو التركيز على تصميم وتقييم أداء جهاز الاستشعار بالسعة التفاضلي مع دمج مصادر متعددة من حاصدات مختلفة كمصدر للطاقة. كما تمت دراسة التوصيف الكهربائي لأداء الجهاز في هذا البحث. وتتطلب دائرة المحول التفاضلي للسعة إلى الجهد (CVC التفاضلي) المقترحة إمداداً واحداً من حاصدة الطاقة الذي تم تنفيذه باستخدام تقنية هجينة والتحقق منه من قبل المكونات المنفصلة. وقد أظهرت النتائج مدى واسع من الكشف من 2-23 بيكو فاراد، والنتيجة الأفضل سجلت في تردد 200 كيلو هرتز، والجهد الناتج قدره 1.5-2.22 فولت. تم تحقيق ذلك من خلال ذلك من خلال تنفيذ إمداد طاقة قدره 3.3 فولت، مع متسعة الكشف الاسمي  $Cx0 = 5$  بيكو فاراد. استهلكت الدائرة 3.83 ميغا واط من الطاقة، وهو تحسن 28.9% عن النتيجة السابقة. بوجود أو بدون وجود السعة الطفيلية، أظهرت الدائرة المقترحة مستوى عال من الخطية في قيمة R-تربيع تصل إلى 0.99944 باستخدام متغير سعة قدره 0.1 بيكو فاراد مع حساسية قدرها 0.05431 ميغا فولت لكل فمتو فاراد تغيير عبر تردد يتراوح بين 40 كيلو هرتز إلى 400 كيلو هرتز. تحسنت الحساسية بنسبة 43% مقارنة بالعمل السابق. وقد أظهرت المقارنة بين النتائج التجريبية والنظرية فرقاً قدره 5%. وكذلك تناسب الدائرة المقترحة للمحول التفاضلي للسعة إلى الجهد (CVC التفاضلي) لاستخدامها كنقطة استشعار في المنطقة التي تقلل من وصول الإنسان لاستبدال البطارية ومناسبة لدمج استشعار الضغط والتسارع للنظام.

## **APPROVAL PAGE**

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## LIST OF SYMBOLS

$\hat{V}_{ext}$	Excitation voltage amplitude after modulation
+Vs	Positive rail of the Opamp
$2 \phi_F $	Surface inversion potential
$\text{\AA}$	Amstrong
A	Area of plates
$A_d$	Differential gain
C	Capacitance, (in farads, F)
$C_d$	Rectifier/low-pass filter capacitor
$C_{p1}$	Parasitic capacitance at one side of $C_x$ electrode
$C_{p2}$	Parasitic capacitance at one side of $C_x$ electrode
$C_{p3}$	Parasitic capacitor parallel to $C_x$
$C_r$	Reference capacitor, value is fixed.
$C_x$	Feedback capacitor
$C_x$	Sensor capacitor
$C_{x0}$	Nominal capacitor
d	Distance between parallel plates
E	Electrical field (in volt per meter, $V \cdot m^{-1}$ or newton per coulomb, $N \cdot C^{-1}$ )
$\epsilon_0$	Electric Constant ( $\epsilon_0 \approx 8.854 \times 10^{-12}$ F/m)
$\epsilon_r$	Dielectric constant or relative static permittivity of material
F	Force (in Newton, N)
$f_{ext}$	Excitation frequency
$f_{sensor}$	Sensor frequency

$G$	Gain
$gm$	Transconductance
GND	Ground
Inamp	Instrumentation amplifier
$m$	Multiplier numbers to the excitation input voltage, $V_{ext}$
$n$	Multiplier numbers to the excitation input voltage, $V_{ext}$
$Q$	Charge (in Coulomb, C)
$R_A$	Parasitic resistance in the cable
$R_d$	Rectifier/low-pass filter resistor
$R_f$	Feedback resistor
$R_G$	Gain resistor
$R_p$	Parasitic resistance parallel to the sensor $C_x$
$V$	Voltage (potential) difference between two plates
$V_{ext}$	Excitation voltage
$V_{out\_A}$	Output voltage from <i>opamp A</i>
$-V_s$	Negative rail of the Opamp
$V_s$	Source from energy harvester
$\Delta C_x$	Changes of capacitance detection
$\varphi$	Magnitude phase angle

## LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog-to-Digital Conversion
AM	Amplitude Modulated
BAN	Body Area Network
C/D	Capacitance-to-Duty cycle
CDC	Capacitance-to-Digital Converter
CFC	Capacitance-to-Frequency Converter
CIS	Capture components Information System
CMOS	Complementary Metal Oxide Semiconductor
CO	Carbon monoxide
COX	Gate-oxide capacitance, per unit area
CPC	Capacitance-to-Phase Converter
CVC	Capacitance-to-Voltage Converter
DC	Direct Current
DM-PEM	Direct-methanol proton-exchange membrane fuel cell
EH	Energy Harvesting
FEM	Finite Element Method
GB	Gain Bandwidth
GBWP	Gain Bandwidth Product
IEEE	Institute of Electrical and Electronics Engineers
IC	Integrated Circuit
IoTs	Internet-of-Things
Li-ion	Lithium ion battery

LoC	Lab-on-Chips
MCU	Microcontroller Unit
NiMH	Nickel Metal Hydride Battery
NMOS	N-type Metal Oxide Semiconductor
Opamp	Operational Amplifier
PAN	Personal Area Network
PM	Phase margin
PMOS	P-type Metal Oxide Semiconductor
PSpice	PC version of Simulation Program for Integrated Circuit Emphasis
PVDF	Polyvinylidene Fluoride
RHP	Right Half Plane
SC	Switched Capacitor
SHM	Structural Health Monitoring
SiNP	Si nanopillars
SMD	SMD Inc. is an electronics and electrical components provider.
TEG	Thermoelectric Generators
TSMC	Taiwan Semiconductor Manufacturing Company
VFC	Voltage-to-Frequency Converter
VPC	Voltage-to-Period Converter
WSN	Wireless Sensor Network

# CHAPTER ONE

## INTRODUCTION

### 1.1 OVERVIEW

Powering electronic components of small portable or implantable devices powered from non-traditional ambient means of energy sources has been the subject of attention over the past recent years. Such energy sources are going to go into waste if not utilized properly. Power supply technology is the most crucial part and used in all electronic equipment. The trend of current society towards personalization and mobilization has required the power supply technology to be light weight, smaller in size, and with high efficiency (Mathúna et al., 2005).

This requirement has gained momentum from its application view point in the field of industrial automation, smart buildings, personal healthcare, logistic and maintenance, military equipment, aerospace, wearable and portable electronic devices (University of Southampton, 2007; National Institute of Standards and Technology (NIST), 2012; Krupenkin & Taylor, 2011; Ramadass & Chandrakasan, 2011; Zhu et al., 2011). Power electronic designs are already on the trend of becoming smaller and more efficient with lesser power requirement. Hence, it is not surprising that the number of activities in investigating techniques for harvesting energy from the ambient sources such as light, radiations and vibrations are on the rise.

On the other spectrum, the Internet-of-Things (IoTs) is already in the market for connecting billions of things unnoticeably embedded in the environment, operating autonomously and communicating wirelessly. An active device requires to be running on small efficient batteries. However, in most ongoing trend of passive and

autonomous cases, the device is running on batteries via energy harvesting means. Such the case for powering nodes in the intelligent sensors networks including Body Area Network (BAN) and Personal Area Network (PAN). These applications require devices to be smaller not only in size and dimensions, but efficient in power requirement too (Harrop & Zervos, 2010).

The move towards wireless communication has made designers to opt from devices supplied by wired power to devices powered by wireless or non-contact means. Devices with less power consumption are usually designed to be light in weight, smaller in size, equipped with energy harvesting means of power supply and have wireless communication capability (Knight et al., 2008). A wireless approach for data communication, though not as reliable as wired approach, is a preferable choice in industrial applications due to limited space or inaccessibility constraint (Chen et al., 2010).

The smart wireless sensor usually is associated with IoTs is an emerging sensor environment with essential features such as on-board micro-processor, sensing capability, wireless communication, battery-less powered system and low-cost maintenance feature. In contra, conventional wireless sensor nodes have used batteries as power supply but the issue of replacing the batteries have contributed to other problems such as time, less autonomous, inconvenience of service interruption caused, tedious job and high operation cost. Therefore, it is favourable to design a wireless sensor node relying on self-generated power from ambient sources such as vibrations, heat, water, human activity and wind (Dondi et al., 2008).

## **1.2 BACKGROUND AND MOTIVATION OF THE STUDY**

Capacitive measuring system is an important technology in the transducer system especially in automotive, biomedical, chemical industries and water level measurement application. The motivation behind using capacitive measuring system is that it easily provides an efficient conversion of changes in the parameter of interest into a wide range of capacitance changes, which are in turn changed into proportional voltage or frequency changes. The advantage here is that these conversions take place without functionality loss and most precise compared to other electrical sensors such from using resistive and inductive sensors (Kinney & Baumer, 2011). Unlike inductive sensors that use magnetic field, the object to be sensed must be a conductive or metal object. While capacitive sensor uses electric field to sense object that is either a conductive or non-conductive object. It reacts to changes in capacitance, as long as the object has certain dielectric material, surface area and within the distance of electric field (Zhang et al., 2017).

Capacitive sensor is a promising solution of powering wireless sensor nodes by using the source of vibrations, converting mechanical energy to electrical energy. This method has been comprehensively researched over the recent past years. Among the vibrations transducer methods used are piezoelectric, electromagnetic and capacitive-inductive or capacitive-electrostatic approach (Beeby et al., 2006). The selection of converting device is dependent on either capturing or measuring the physical parameters such as displacement, velocity and acceleration.

Many wireless electronic devices such as tiny wireless sensor network nodes, wireless health monitoring systems, as well as consumer products such as smart phone have severely constrained with power sources (Louisiana Tech University, 2010). The bottleneck of such devices is the provision of sustained power supply without the

requirement of having batteries, needing either being charged up or replaced at the expense of costs and time. Smart wireless powered sensor has been proving cost effective as an alternative tool when realized properly, particularly in electronic devices used in applications such as in the Structural Health Monitoring (SHM) system, monitoring forest fires, medical implants, and oceans pollution spillages, etc (Ling et al., 2009).

Wireless sensing provides the opportunity to install masses of sensors with virtually no cost of installation by limiting the need for cables, more reliable and maintenance free than hard wiring. More sensors mean more process efficiency, lower operating costs, lower maintenance costs, higher reliability and greater safety. While the majority of sensor networks in use today employ a wired architecture, development and deployment of wireless sensor networks has exploded in recent years. Wireless communication protocols are now standardized with such protocols as IEEE 802.11 through 802.15, and bandwidths are now approaching that of conventional wired networks. Furthermore, increases in processor production capability have reduced the power requirements for both computing and communication. In fact, sensing, communication, and computing can now be performed on a single chip, reducing the cost further and permitting economically viable high-density sensor networks (Harrop & Zervos, 2010).

### **1.2.1 Power or Energy Consumption**

According to (Magno et al., 2013), among the benefit of reducing power consumption is reducing the size of energy harvester devices at wireless node. In consequent, reduces the overall cost of the system. In any wireless activity, radio transceiver or transceiver activity is the most power hungry component in wireless sensor node. By

reducing this activity, the total power consumption of the system could be reduced. It is important to reduce power requirement whether the power is from energy harvester or from batteries especially in portable device applications like computing devices, medical implants, military equipment, wireless sensor network, and IoTs. Most of current research has focused on microwatt to hundred milli-watt range of power output energy harvesters (Beeby et al., 2006). Figure 1.1 shows very clear trend, that the smaller the device size is, the smaller its power requirement becomes.

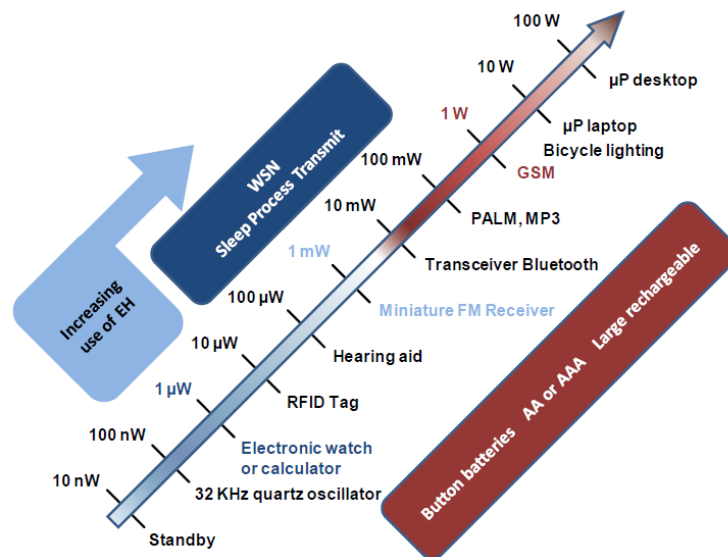


Figure 1.1 Power Needs for Small Electronics (Harrop & Zervos, 2010)

This minimum power requirement shows that it is suitable for modern devices to harvest energy from environment such as from vibrations, heat and light. However, few attempts of research have been made on the medium range power output especially suitable for mobile applications using energy harvester techniques. Efficiency of the power output of energy harvester is significantly limited by the effectiveness of the energy converting transducers used for energy conversion.