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CAPACITANCE MONITORING SYSTEM FOR ELECTROSTATIC WIND ENERGY HARVESTER

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Abstract

In this paper, a capacitance monitoring system for electrostatic wind energy harvesters has been proposed. First, the operation of the harvester and the harvesting cycle is explained in details. Second, the capacitance monitoring system is demonstrated. Third the simulation and experimental testing of the monitoring system is presented. The capacitance monitoring system requires a microcontroller to sense the change in capacitance and to provide controlling signals to operate the harvester during the harvesting cycle. Results of the testing proved successful operation of the monitoring system in detecting capacitance variation with time.

Keywords

Capacitance monitoring systems, Electrostatic harvester, Low power microcontroller, Wind energy.

1. Introduction

Energy harvesting is the process by which energy is derived from external sources, captured, and then converted into usable electrical energy. The driving force behind the search for new energy harvesting devices is the desire to power wireless sensor networks and portable devices without batteries (Boisseau & Despesse, 2012). The surrounding environment is a rich source of energy, from solar, thermal to kinetic. There are many types of energy harvesters are described in the literature (Boisseau & Despesse, 2012). One possible structure which is presented in this paper is the electrostatic harvester that can extract kinetic energy from wind using variable capacitors. The electrostatic devices are self-biasing, and can directly charge batteries, or can produce exponentially growing voltages on storage capacitors, from which energy can be periodically extracted by DC to DC converters (Torres, Gabriel & Mora, 2009a), (Roundy, Wright, Kristofer& Pister, 2002). To operate the electrostatic harvester, capacitance monitoring system is required. The capacitance monitoring system is considered as an essential part of any electrostatic harvesting system as it is required to repetitively monitor the change of capacitance during the harvesting cycle. Various methods are used to sense and monitor capacitance, such as mechanical, optical, magnetic and electric circuit (Webster, 1999). The aim of this paper is to present the operation of an electric based capacitance monitoring system during the harvesting cycle. First the construction and operation of the capacitance monitoring system is demonstrated. Second, the simulation and the experimental testing is presented and finally, summary of the results are demonstrated.

2. Electrostatic Wind Energy Harvester

The electrostatic-based wind energy harvester is a unique system the combines the concept of electrostatic and wind effect together. The design and the operation of the harvester has been proposed previously in (Rita, Luay & Paul Ivey, 2015). The first stage of power conversion is from wind energy to mechanical power, using a micro wind turbine. The second stage is the conversion of rotational mechanical power to electrical power using the electrostatic converter, which consists of a variable capacitor, energy transfer circuit, capacitance monitoring system and a controller as illustrated in Fig.1. The variable capacitor used is a variable multi-pole capacitor made of two parallel plates: rotor and stator. Each rotor and stator is divided into a number of poles. The number determines the amount of capacitance variation within a single rotation. The energy transfer circuit is an LC to LC circuit that operates under a voltage constrained mode (Boisseau & Despesse, 2012). It has three phases to complete a harvesting cycle: pre-charge, harvest and reset (Torres, Gabriel & Mora, 2009b) and the controller acts as a capacitance monitoring system and a controlling device.

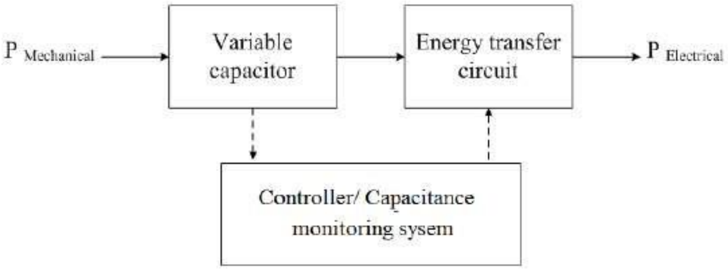

Figure 1: *Block diagram of the electrostatic converter*

3. Energy Harvesting Cycle

The energy harvesting cycle is divided into three phases: pre-charge, harvest and reset phase, as shown in Fig. 2. The pre-charge phase starts when the variable capacitor is at maximum capacitance. During this phase, the capacitor is charged to maximum voltage of the battery of the LC to LC circuit (Fig.3), which represents an energy investment from the battery.

$$E_{inv} = \frac{1}{2} C_{max} V_{Bat}^2 \quad (1)$$

As capacitance starts decreasing, the harvesting phase starts and charges flow into the battery producing a harvesting current, which enables energy to be harvested and stored.

$$I_{harv} = \frac{dq}{dt} = V_{Bat}\left(\frac{dC_{var}}{dt}\right) \quad (2)$$

$$E_{harv} = \int V_{Bat} I_{harv}(t)dt = \Delta C_{var} V_{Bat}^2 \quad (3)$$

During the reset phase, capacitance falls to its minimum and, since the voltage is constant, it retains remnant energy (Torres, Gabriel & Mora, 2009b). The energy stored in the capacitor at minimum capacitance is simply:

$$E_{rem} = \frac{1}{2} C_{min} V_{Bat}^2 \quad (4)$$

As a result of the harvesting cycle, a net theoretical energy gain is generated (Torres, Gabriel & Mora, 2009b):

$$E_{net} = -E_{inv} + E_{harv} + E_{rem} \quad (5)$$

$$E_{net} = \frac{1}{2}\Delta C_{var} V_{Bat}^{2} \quad (6)$$

Equation (6) shows that theoretical net energy depends on variation in C from maximum to minimum capacitance, and the battery voltage. Since the battery voltage is fixed to a certain extent as it is application dependent, then the C_{var} variation is the only element that decides the amount of harvested energy. This means more energy can be harvested when the cycles goes faster. However, there is a physical limit based on the time required to complete the pre-charge phase.

4. Capacitance Monitoring Systems

Since the harvesting cycle mainly depends on the capacitance value, as demonstrated previously in Fig.3, the capacitance monitoring system is considered as an essential part of the harvesting system.

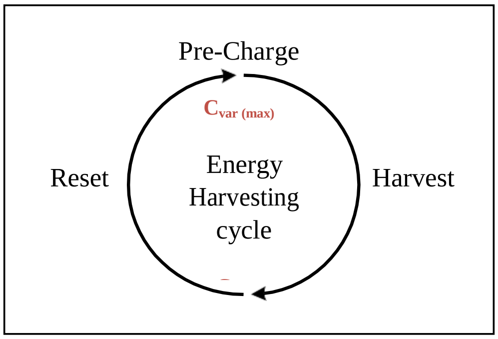

Figure 2: *Energy harvesting cycle* (Torres, Gabriel & Mora, 2009b)

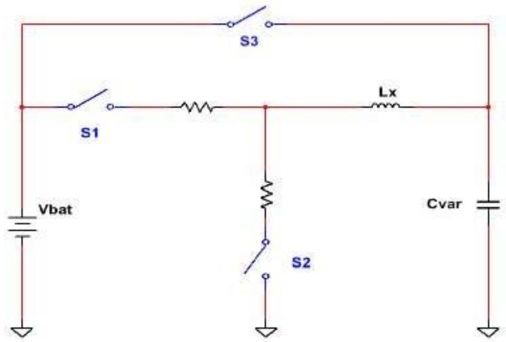

Figure 3: *LC to LC energy transfer circuit*

Various methods are used to sense and monitor capacitance, such as mechanical, optical, magnetic and electric circuit (Webster, 1999). The mechanical method involves allowing brushes to sense the position of the conductive plates of the movable part of the capacitor. Some drawbacks with this method are that the brushes wear out after a certain time period and that they cannot operate in a rough environment. Moreover, the mechanical systems require high power to operate. The optical method is to send light through the plate using a light-emitting diode and to detect the light coming out the other side with a photo diode. The drawbacks with this method are that dirt and dust can interfere with the light and that this method also consumes a lot of power as it is has to be permanently operational. The magnetic method can use a variable reluctance sensor or an inductive proximity switch. Both methods are based on magnetic or magnetic absorbing material. One drawback with this method is that other external magnetic sources can create interference with the sensor, which reduces the sensing accuracy. Additionally, the sensing devices used in this method are not cost effective.

While various circuits can be used in the electric method, such as capacitive bridge detector, capacitive pseudo bridge or an RC oscillator. These circuits depend on capacitance variation to measure the voltage, frequency or time period. The advantage of using the electric circuit is that it can be designed to operate successfully with very low amount of power consumption. Oscillators being found the most suitable for the wind harvesters as they are simple circuit, very accurate in measuring capacitance values and consumes very little power. The basic idea of using oscillators is to generate signals of variable frequencies that depend mainly on the capacitance variation of C_{var}. While many oscillator circuits are suitable for capacitance measurement, the most suitable one for an electrostatic harvester is the RC oscillator. The RC oscillator is a comparator circuit. The output signal of its oscillator has a frequency. Its frequency value depends on the values of the resistor and capacitor of the oscillator circuit Rx and C_x, as shown in Fig.4. The three resistors R_1, R_2 and R_3 set the threshold voltages when the comparator output signal switches. The oscillation time period is set by the values of Rx and C_x. Since Rx is set to a fixed value, the only factor that changes the frequency and the time period is C_x, which is the C_{var} of the harvester as illustrated by equation (7) (Seek-ic, 2012).

$$f = \frac{0.72}{R_x C_{var}} \qquad (7)$$

As a result of the capacitance variation, the maximum and minimum capacitance can be detected to allow the LC to LC energy transfer circuit to start the harvesting cycle.

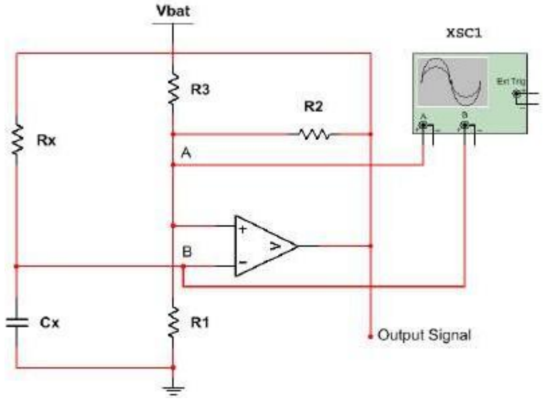

Figure 4: *RC comparator oscillator for capacitance measurement*

5. Low Power Microcontrollers

The controller is a critical part of the harvester system. In the electrostatic-based wind energy harvesting system, the controller is responsible for sending signals to control the operation of the switching devices. The controller has both input and output ports. It receives input from the capacitance monitoring device and then, based on the capacitance value (maximum or minimum); it sends a control signal to operate one of the switching devices of the LC to LC circuit. The power consumption of the microcontrollers is a very important factor when dealing with energy harvesting because it is essential for the microcontroller to consume as little power as possible while providing functions that reduce the overall system's power consumption. Currently, two extreme low power technologies are available: nano Watt and nano Watt XLP (Ivey, 2009). There are two main factors affecting the power consumption of the two technologies: dynamic and static power. Dynamic power is the power consumed by the switching of digital devices while static power is the power consumed by disabling the main clock using leakage transistors. The primary requirement for a low power microcontroller is the power consumed while in sleep modes. There are three basic low power modes of operation:

Sleep, low voltage (LV) sleep and deep sleep. Fig.5 shows the current consumption of various modes of operation. Sleep mode is used when the application requirement is to sleep most of the time, wake every second to process information and then go back to sleep. Low voltage sleep mode is most likely to be used when the requirement is to sleep most of the time, wakeup for few seconds to process data then go back to sleep. Deep sleep mode is to sleep most of the time but wakeup to process information once every hour, day, etc (Microchip, n.d.).

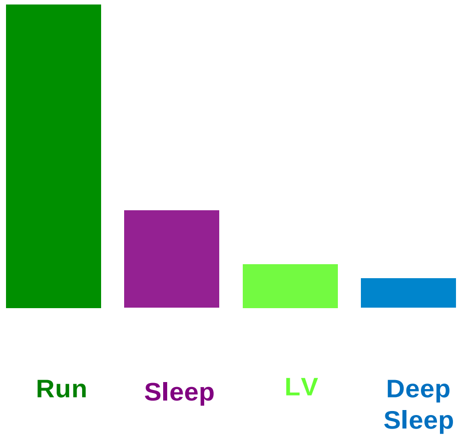

Figure 5: *Microcontroller current consumption during various modes of operation (Microchip, n.d.)*

Table 1 shows various types of extreme low power microcontrollers and typical current values during sleep mode and deep sleep mode. Note that all figures are typical values at minimum V_{dd} taken from the microcontrollers' datasheets. For an electrostatic-based wind energy harvester, the typical operation modes are run and sleep modes so the most suitable microcontroller device is PIC18LF45K50 as it has the lowest current consumption during the sleep mode. Since capacitance value is an important factor in starting the pre-charge, harvest and reset phases, the harvester controller is needed to measure the capacitance. The main method for measuring capacitance is to use the internal comparator of the microcontrollers. The comparator can be used to build the RC oscillator, as described in section IV. The main reasons for using the microcontroller's comparator for the oscillator circuit are that it has a better comparator than many dedicated comparator ICs and that its output has good push-pull low resistance FETs. As C_{var} varies, the controller measures the time period very precisely. Then a simple calculation is performed to scale the time period to a specific capacitance value. If the controller detects the maximum capacitances range, it sends a signal to start the pre-charge and harvest phase. When the range of minimum capacitances is detected, the harvest phase ends and the rest phase starts.

MCU with XLP Technology	**Pins**	**Sleep (nA)**	**Deep Sleep (nA)**	**µA/MHz**
PIC16F1823	8/14	20	-	34
PIC16F1509	20	25	-	30
PIC18LF45K50	28/44	10	-	110
PIC18LF47J13/J53	28/44	200	9	197
PIC24F16KL402	14/20/28	30	-	150
PIC24FJ64GB004	28/44	200	20	250
PIC24FJ128GA310	64/100	330	10	150

Table 1: *Extreme low power XLP microcontrollers (Microchip, n.d.)*

During the harvesting cycle, the microcontroller produces three control signals, S1, S2 and S3, as given in Fig.6 which control the operation of the three switching devices. During the pre-charge phase, a control signal S1 goes high in order to close sw1 for a short time period. After a small delay, control signal S2 goes high to close sw2 in order to continue charging C_{var}. The delay is included between every switching transition to prevent short-circuit conditions and high peaking voltages. Control signal S3 then goes high to start the harvesting of energy by closing sw3. Figure 7 demonstrates the operation cycle of the harvester with three control signals. Additional role of the controller is to operate and send information about wind speed if an RF transmitter is used to transmit information about the detected wind speed. When the controller detects maximum capacitance, it sends a signal to the transmitter before starting the pre-charge phase. Once minimum capacitance is detected, it sends another signal to the transmitter before starting the reset phase. As long as wind is available, the transmitter keeps sending trigger signals to the receiver side, which will then calculate the time taken between the two trigger signals and calculate the detected wind speed.

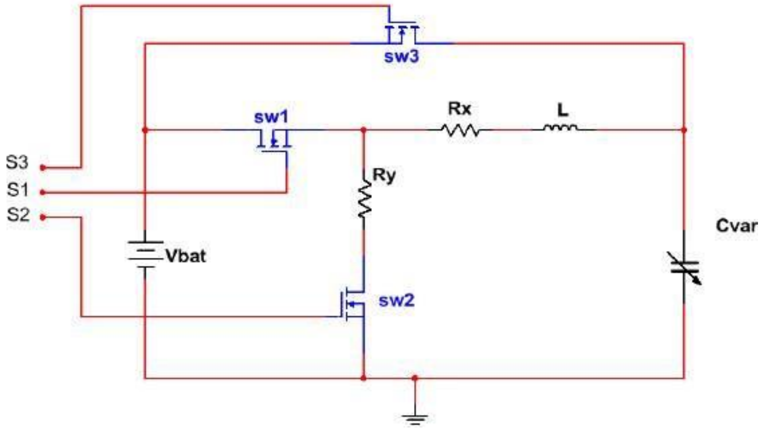

Figure 6: *LC to LC energy transfer circuit with S1, S2 and S3 control signals*

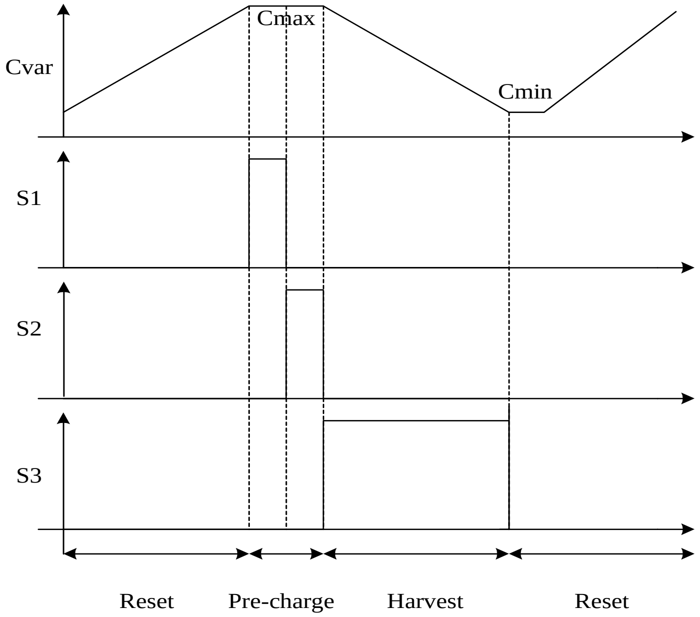

Figure 7: *Operation cycle of the harvester with S1, S2 and S3 control signals*

The flow chart in Figure 8 summarises the operation of the controller used in the electrostatic-based wind energy harvesting system. T_{sleep} is the time period of the controller sleep mode; $T_{Energize}$ is the time required to charge the inductor L; $T_{D\text{-}energize}$ is the time required to discharge the inductor L to C_{var}.

6. Simulation of the Capacitance Monitoring Circuit

In principle, the capacitance monitoring circuit can be simulated using several software tools such as Multisim, Matlab/ Simulink, ISIS Proteus or Spice. However, Proteus software was chosen as the simulation platform because it is capable of accurately simulating the capacitor monitoring circuit using the PIC micro controller. The complete circuit of the capacitance monitoring system is given in Fig 9.

7. Experimental Testing

A photograph of the variable capacitor experimental setup in the electronics laboratory is shown in Fig 10. The physical dimension of the capacitor is 85 mm × 145 mm × 85 mm. When wind blows at the harvester, DC current is generated and directed into the Lithium ion battery by the LC to LC energy transfer circuit. The capacitance was measured using the GW-INSTEK 816 LCR meter as shown in Fig10. The minimum and maximum capacitances of the variable capacitor were measured as 168 pF and 430 pF.

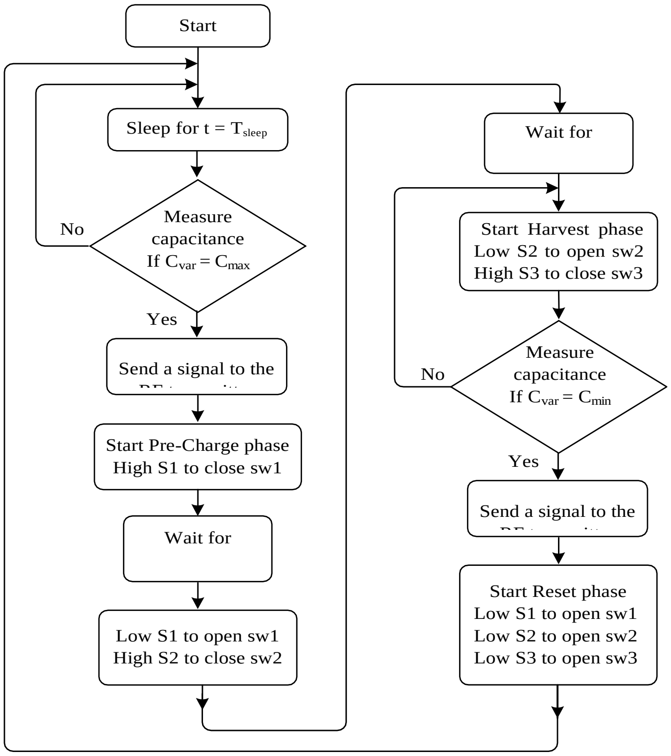

Figure 8: *Flow chart of the controller operation*

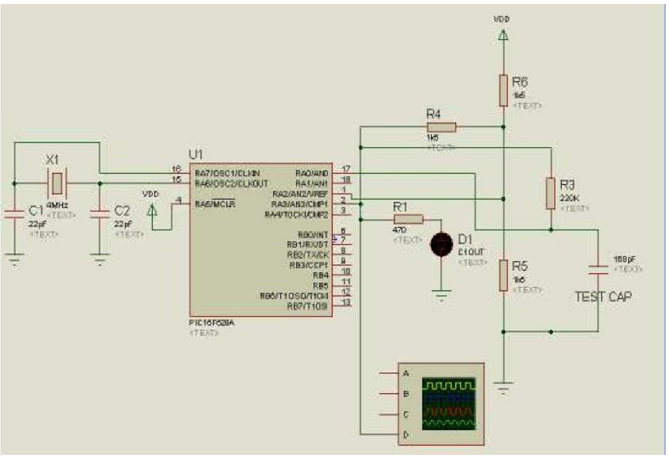

Figure 9: *Capacitance monitoring circuit using PIC microcontroller*

The capacitor used is a two pole capacitor capable of harvesting energy twice within a single rotation. The results of the capacitance measurement are shown in Fig. 11.The oscillator circuit is used for monitoring the capacitance in this setup. Whenever the circuit detects the maximum capacitance C_{max}, a signal is sent to the controller to start the pre-charge phase followed by the harvesting and the reset phases. Before the start and the end of the harvesting cycle, the microcontroller sends signals to the RF transmitter. The data is then used to calculate the wind speed that would be detected by a receiver. The experiment setup as illustrated in Fig 12 is to show the basic operation of the capacitance monitoring system which is controlled by the PIC microcontroller. The variable capacitor was connected permanently to the digital storage oscilloscope to capture the charging and the discharging of the capacitor during the harvesting cycle. The RF transmitter used is AM-RT4-433FR (Tan & Panda, 2007) connected to the 16F82A PIC microcontroller through 2N7000 transistor.

Figure 10: *Photograph of the variable capacitor prototype and the LCR meter*

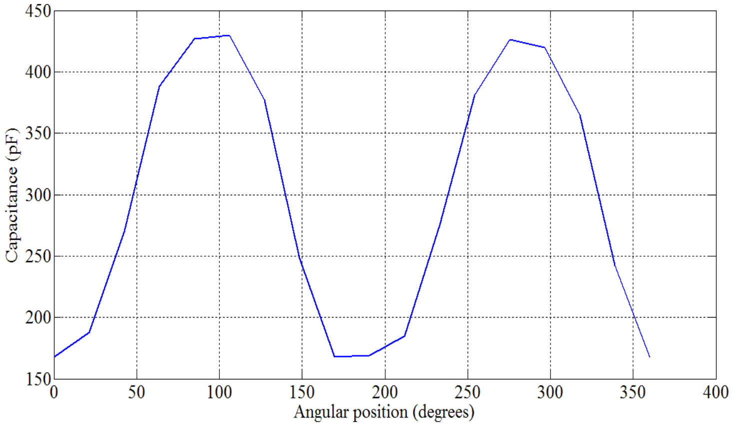

Figure 11: *Capacitance variation with angular position for the prototype device*

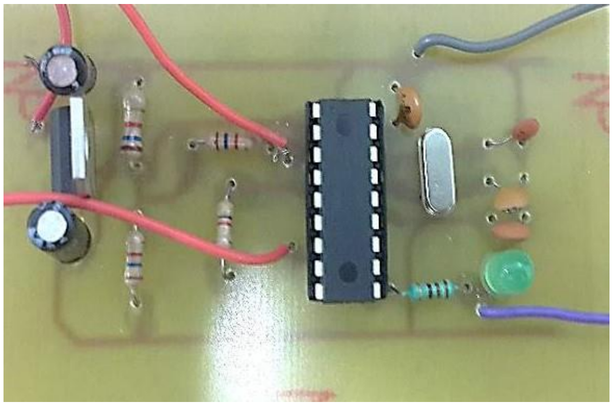

Figure 12: *Photograph of the capacitance monitoring circuit using PIC*

8. Results

Simulation

Simulation was conducted to test the oscillator at various capacitance values. Figure 13 shows the results of the testing. Three signal with different frequencies was generated starting from minimum, mid and maximum capacitance. Figure 14 shows the calculated values of frequencies at the same capacitance values. It is clear that there are small differences due to simulation error.

Experiment

The power consumption when no change in capacitance is detected is around 0 W since the PIC is programmed to switch to sleep mode when no wind is detected. During the run mode of operation, the power consumed is less than 5mW. Figure 15 shows the output signal of the oscillator at various frequencies. The similarity of the results of the simulated, calculated and measured data give confidence in the accuracy of the experiment.

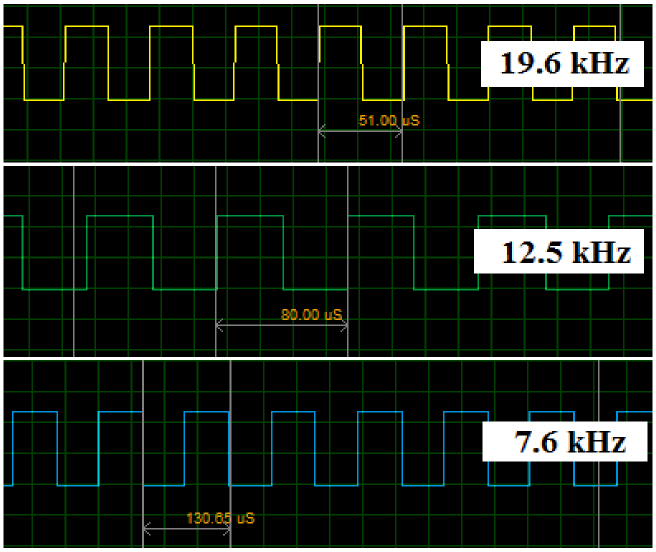

Figure 13: *Results of simulation testing*

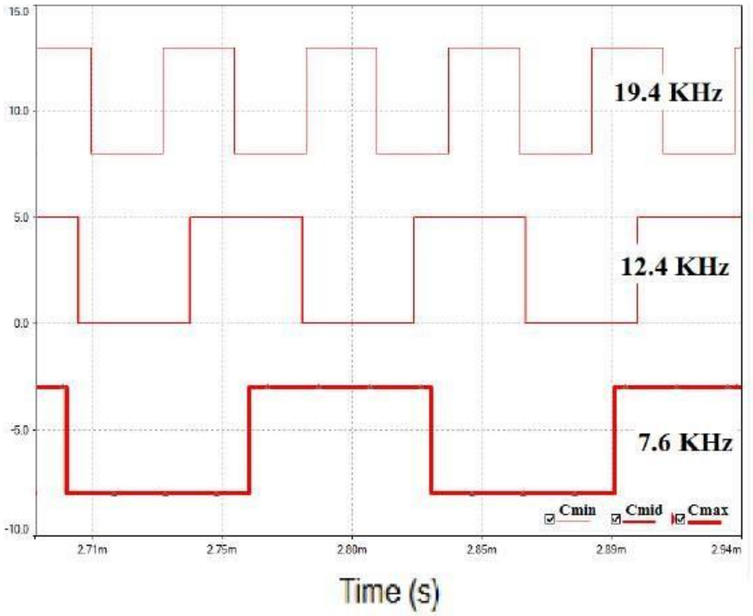

Figure 14: *Results of calculation*

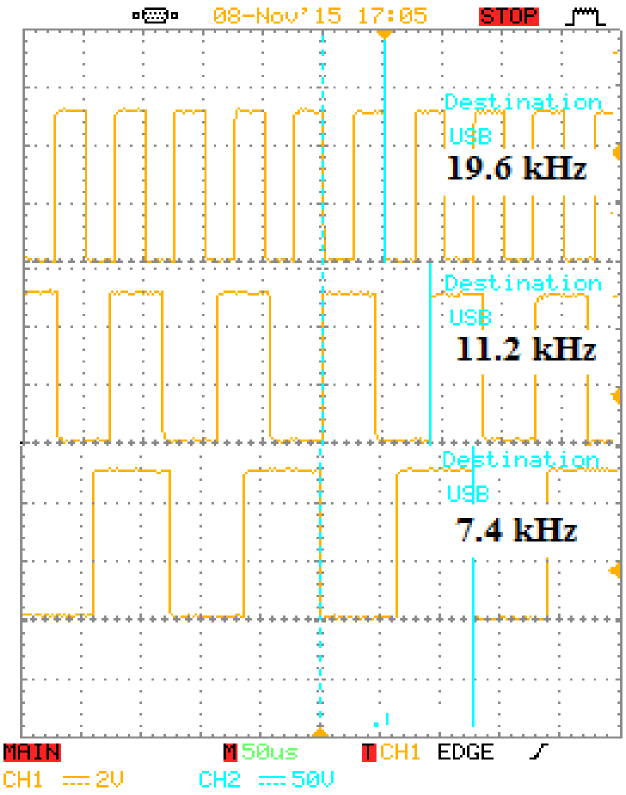

Figure 15: *Results of experimental testing*

Conclusion

RC oscillators are found to be the most suitable monitoring system for the wind harvesters as they are simple circuit, with high accuracy in measuring capacitance values and consumes very little power. The basic idea of using oscillators is to generate signals of variable frequencies that depend mainly on the capacitance variation of C_{var} which was used to detect minimum and maximum capacitance to operate the harvester. Results of the experiment and simulation proved that a small changes in the capacitance can be detected easily using the oscillator circuit. While many oscillator circuits are suitable for capacitance measurement, the most suitable one for an electrostatic harvester is found the one built using the internal comparator of low power microcontrollers. The low power microcontrollers are considered as the best controlling mechanism as it can be easily programmed and reconfigured to fit any capacitance requirement. It also consumes little power in both run and sleep mode. As a summary, this paper proves that off-the-shelf low power microcontrollers can be considered as an excellent choice for electrostatic harvester as it can be used not only as controller device but also a capacitance monitoring system.

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