Simulation and experimental modeling of a multipoles variable capacitor for an electrostatic wind energy harvester

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Abstract: The aim of this work is to study the effect of rotational motion generated by wind on the capacitance variation of the multipole variable capacitor. AutoCAD software was used to model the variable capacitor and to calculate the capacitance variation relative to the angular position caused by wind. Subsequently, experiments were carried out to measure the capacitance variation relative to the angular position and the transient response. Torque analysis was conducted to ensure that the torque applied by wind on a micro-wind turbine could be successfully transferred to the rotary variable capacitor of the harvester. The simulation results indicated a variation of capacitance from 83 pF to 0 pF and the experimental results indicated a variation of capacitance from 110 pF to 39 pF. The torque analysis showed that the torque applied by the wind could successfully rotate the capacitor using a speed-increasing gearbox.

Key words: AutoCAD simulation, electrostatic harvester, variable capacitor, wind energy

1. Introduction

Electrostatic harvesters are used to extract energy from the environment and can be employed to power small devices that require a low amount of power, such as remote sensor networks, mobile phones, media players, digital cameras, and iPods [1,2]. Although high-energy batteries are commonly used in devices, these batteries have a number of disadvantages. They are usually large in size, they have a limited lifetime, they contain a finite amount of energy, and they include chemicals that can be toxic to the environment [1,2]. As an alternative, power can be harvested from wind using an air variable capacitor.

Variable capacitors are the key elements in electrostatic energy harvesters [1,3], and they usually harvest power in three main steps: (a) capturing wind energy and converting it to mechanical power using a micro-wind turbine, (b) converting mechanical power into electrical power using a multipole variable capacitor with the aid of the converter circuit, and (c) processing and storing the electrical energy in a storage device [2,4]. Various variable capacitor realization methods have been reported in the literature, including in-plane overlap, in-plane gap closing converter, and out-of-plane gap closing converter [2–12]. In similar studies, the source of energy used is vibration energy with a linear motion mechanism. Furthermore, it is observed that the in-plane overlap converter mechanism can produce a higher amount of energy per unit volume as compared to the other two mechanisms [7,10]. As a result, the best option is the variable area method with rotational motion applied from wind. This would help in generating reasonable power from wind power based on a similar construction to the variable capacitor machine reported in [3]. In our previous paper, various types of...
variable capacitor realization methods were compared [13]. In addition, the performance of a specific type of macroscale electrostatic harvester system linked to a micro-wind turbine was investigated [14,15]. The proposed harvester was made of a multipole rotary capacitor and a converter circuit. The rotary capacitor was replaced in Simulink/MATLAB by a theoretical model based on the assumption of a linear capacitance variation between the maximum and minimum capacitance. Simulation results indicated that the maximum harvested average power was 4.76 mW at a wind speed of 10 m/s with harvested energy of 3019.28 \( \mu \)J per second [15]. Further research was required to present an in-depth study of the variable capacitor used for the wind harvesting system.

The purpose of this research was to study the effect of rotational motion generated by wind on the capacitance variation of the multipole variable capacitor prototype. The focus of the work was to extract the actual model of the capacitor using AutoCAD’s capacitance calculation, as well as practical experiments. Both approaches were based on varying the capacitor rotors at various angular positions and measuring the corresponding values of the capacitance. The model was determined using a MATLAB curve fitting tool. In addition, an analytical method was carried out to ensure that the torque on the micro-wind turbine could be successfully transferred to the rotary capacitor. The results obtained from the simulation and experiments were compared in order to confirm that the prototype capacitance variation is in good agreement with the simulation. The comparison also helped identify the parasitic effect on the prototype capacitance.

2. Multipole variable capacitor

2.1. Variable capacitor profile

Figure 1 illustrates the 3D AutoCAD model of the multipole rotary variable capacitor described in our previous paper [8]. The model is different from those used in previous studies [2–12] in that it provides a higher amount of power, a higher capacitance variation, and less fringing [3]. The capacitor is constructed from a rotor and a stator. The stator consists of 8 sets of arrow-shaped plates, as shown in Figure 2. Each set consists of an array of 9 plates separated by air as a dielectric material. The rotor consists of a set of 9 rectangular rotating plates. The system of the two opposite stator sets and all rotor plates is called a pole. Each pole produces a specific amount of power during energy harvesting.

As described in Section 1, different types of electrostatic capacitors were studied. Their capacitance variation relied on modifying either the area of the capacitor plates \( A \), the distance between them \( d \), or the dielectric constant of the insulation material between the plates \( \varepsilon \), based on the following capacitor equation
This paper introduces a new type of electrostatic harvester that relies on modifying the area in a multipole variable capacitor. The area of the capacitor plates is a critical parameter for the present computation of the minimum and maximum capacitance, and it has a strong relationship with the amount of harvested power.

2.2. Governing equation

Figure 3 indicates a parallel-plate capacitor that consists of two conducting plates of Area $A$ separated by distance $d$. When the capacitor is charged, the plates hold identical amounts of charge: one plate carries the positive charge and the other one carries the negative charge [16]. If the plates are large, then the charges can be distributed over an extensive area, and, as a result, the amount of charge that can be stored on a plate for a given constant amount of voltage increases as $A$ is increased. Thus, the total capacitance is proportional to the effective area of the plates and is calculated as in Eq. (2) [7]:

$$C = \varepsilon \left( \frac{A_{\text{effective}}}{d} \right),$$

where $A_{\text{effective}}$ is the area projected from one plate onto the other and $d$ is the distance between the parallel plates.

The capacitance of this multipole capacitor is determined as a function of the angle of rotation $\theta$. The highest capacitance is reached when the angle of rotation is zero. When there are two plates in each comb, the number of neighboring sheets of positive and negative charge is 3, as Figure 4 shows.

In general, when there are $N$ plates on each comb, the number of parallel capacitors is $(2N - 1)$ and the total capacitance is [16]:

$$C = \frac{(2N - 1) \varepsilon A_{\text{effective}}}{d/2}.$$  

2.3. Variable capacitor material

In general, most of the capacitor plates are made of conducting materials (metals). In addition to being conducting, the capacitor plates need mechanical strength and resistance to corrosion from the environment.
Other requirements include cost, as the material should be inexpensive and should have good availability to be suitable for production. As a result, different materials are usually used for capacitor plates, such as aluminum, silver, brass tantalum, and carbon nanotube [17]. The proposed variable capacitor plates are made of aluminum and the inner rod is made of stainless steel. Aluminum is inexpensive and highly conductive, and it can be easily formed into plates. The inner rod or screw is made of stainless steel, due to the great resistance to weather and corrosion of the latter, and for the purpose of electrical conduction.

2.4. Capacitor AutoCAD model

The effective area of the capacitor plates were calculated using AutoCAD. The dimensions of the rotating plates are 155 mm × 18 mm × 0.4 mm and the nonrotating plates consist of 8 arrow-shaped plates pointing to the center. The dimensions of the plates are shown in Figure 5. These arrow-shaped plates were held together by a disk with an inner radius of 81 mm, an outer radius of 91 mm, and a thickness of 0.85 mm. The variable capacitor was modeled with the initial angle of the rotating plates set at 0°. The maximum effective area was then measured by applying a rotation of 1° to the rotating plate, recording the effective area, and iteratively repeating the process for rotations of 0° to 359°. A sample of the process is shown in Figure 6 at an angle of 5°.

The recorded data were then processed using MATLAB, where the capacitance of the variable capacitor was calculated at each degree using Eq. (3). Note that AutoCAD provides theoretical values without considering any parasitic or fringe effects. These effects can only be measured from the experimental testing of the prototype. It can be added as an external constant capacitance parallel with the calculated variable capacitor in Simulink [2,16].

![Figure 5. Arrow-shaped capacitor plate dimensions.](image1)

![Figure 6. Sample of AutoCAD process at an angle of 5°.](image2)

2.5. Model validation

Two experiments were conducted to test the variable capacitor prototype and to validate the AutoCAD simulation results. The experiment setups are shown in Figure 7. The first experiment used a GW Instek
816 LCR meter and an angular measurement disk to measure the total capacitance at every 5° of rotation. In order to rotate the rotor, a motor was connected to it to provide a stable rotational motion. To verify the rotor position, a measurement disk was attached to the stator. The LCR was then set to the fast automatic mode to be able to measure the variation of capacitance values at every 5° of rotation.

The second experiment uses a digital storage oscilloscope GW Instek GDS 2102 and a pulse generator to test the transient response of the variable capacitor.

A pulse waveform from the generator was applied to a 10-kΩ resistor connected in series with the capacitor set at both a maximum and a minimum value. The output was measured across the resistor to find the time constant and the transient response of the capacitor.

3. The micro-wind turbine linked to the variable capacitor

Figure 8 illustrates the micro-wind turbine, the gear box, and the variable capacitor model. The micro-wind turbine was connected to the shaft of the variable capacitor through the gear box. The gear box was used to step up the low angular speed of the turbine to a high rotational speed.

Using the micro-wind turbine has several advantages. Apart from being capable of generating mechanical power from wind speeds lower than 2 m/s, it is small in size with a rotor diameter less than 50 cm. Moreover, its primary cost is not very high, and it is suitable for many low-power applications such as an electrostatic harvester [18,19].

In this research, the micro-wind turbine used was a fan-type blade that had a key advantage of increased power efficiency as compared to an airfoil type. The specifications of the selected wind turbine are given in [18]. The maximum power efficiency of the 8-blade turbine indicates that the transformation of kinetic wind energy to mechanical energy is about 12% at a wind speed of 7 m/s [18]. In the case of extremely high wind speeds, a feedback control system is required to shut down the system until the wind speed goes down to operational range.
4. Torque analysis

In order to analyze the system, the variable capacitor moment of inertia was calculated. Analysis and simulation were used to calculate the inertia. The analytical approach required three steps. First, the dimensions of all the rotating objects such as the head of the inner rode, the rest of the inner rode, the rings between the plates, and the arrow-shaped plates were measured. Note that none of the objects were considered flat. Second, the moments of inertia of all the objects related to the axis of rotation passing through the center of mass and being perpendicular to all plates were determined using Eq. (4):

\[ I_i = \int \rho(x, y, z) d(x, y, z), \]

where \( \rho \) is the volume of the rotating object, \( \rho \) is the density of the material at any given point \((x,y,z)\), and \( d(x,y,z) \) is the distance between any given point \((x,y,z)\) to the axis of rotation. Third, the total inertia of the variable capacitor using the principle of superposition was calculated.

![Figure 8. Micro-wind turbine, gear box, and the variable capacitor.](image)

In the simulation approach, the AutoCAD function MASSPROP was used. It gives the moment of inertia of the object relative to the axis of rotation parallel to the axis at \( x, y, \) and \( z \) and passes through the center of mass. Applying Newton’s second law for both the micro-wind turbine and the capacitor shafts, the following equations can be written [20]:

\[ T_T - T_L = I_T (d\omega_T/dt), \]

\[ T_H - T_C = I_C (d\omega_C/dt), \]

where \( T_T \) is the turbine torque applied by the wind, \( T_L \) is the transmitted torque on the low-speed gear applied by the high speed gear, \( T_H \) is the transmitted torque on the high-speed gear applied by the low-speed gear, and \( T_C \) is the resistance torque on the rotor of the capacitor applied by the stator. \( I_T \) and \( \omega_T \) are the moment of inertia and the angular velocity of the micro-wind turbine, respectively. \( I_C \) and \( \omega_C \) are the moment of inertia and the angular velocity of the variable capacitor, respectively. Assuming the gear box is ideal with no back latches or losses, and assuming that shafts are rigid, where \( n_1/n_2 \) is the gear box ratio, the following can be written:

\[ (T_L/T_H) = (\omega_C/\omega_T) = (n_1/n_2). \]

From Eqs. (5), (6), and (7), the net torque \( T_{net} \) can be derived as follows:

\[ T_{net} = T_T - T_L - T_C = I_{net} (d\omega_C/dt), \]

where \( I_{net} = I_T (n_2/n_1)^2 + I_C. \)
Eq. (8) indicates that the net torque depends on the moment of inertia of both the turbine and the variable capacitor, the angular acceleration of the turbine, and the gearbox ratio. Since $I_{\text{net}}$ is positive and the angular acceleration $\frac{d\omega_C}{dt}$ must be positive for the capacitor to rotate, the following can be written.

$$T_T \left( \frac{n_2}{n_1} \right) - T_C > 0 \text{ or } T_T > \left( \frac{n_1}{n_2} \right) T_C$$

Thus, in order to rotate the rotor of the capacitor, it is necessary for the torque $T_T$ to be greater than $\left( \frac{n_1}{n_2} \right) T_C$.

5. Results and discussion

5.1. Experiment 1: capacitance measurement

Figure 9 indicates the capacitance measurement results of the AutoCAD model and the experiment. Results indicated a sinusoidal relation between the angular position and the capacitance. Moreover, the experimental result showed a higher capacitance than that obtained using AutoCAD, with a maximum difference of 39 pF. To get the mathematical expression of the capacitance in terms of the angular position, the simulation and experimental data points were processed using a MATLAB mathematical curve-fitting tool. The most suitable type of fit for the data points was found to be a Fourier polynomial of degree 1. The resultant capacitance Fourier polynomials for both the AutoCAD capacitance $C_{\text{cad}}$ and the experimental $C_{\text{exp}}$ are given by:

$$C_{\text{cad}} = 37.19 + 40.92 \cos \left( 0.1385x \right) - 2.08 \sin \left( 0.1385x \right),$$

$$C_{\text{exp}} = 75.91 + 34.96 \cos \left( 0.1386x \right) - 2.03 \sin \left( 0.1386x \right).$$

From Eqs. (10) and (11), the difference $C_{\text{diff}}$ can be written as follows:

$$C_{\text{diff}} = C_{\text{exp}} - C_{\text{cad}}.$$
was implemented to validate the experimental results as illustrated in Figure 10. Results of the simulation and the experiment are plotted as shown in Figures 11, 12, 13, and 14, respectively. Simulation results indicated that the settling time was 5.5 μs at $C_{\text{max}}$ and 2 μs at $C_{\text{min}}$. However, the experimental results indicated that the settling time was 8.8 μs at $C_{\text{max}}$ and 5.5 μs at $C_{\text{min}}$. The slight difference in the transient time might be due to the tolerance of the devices and the system parasitic capacitance. The similar shape of the simulated and measured signals gives confidence about the accuracy of the capacitor prototype experiment.

**Figure 10.** Simulink model for capacitor testing circuit.

**Figure 11.** Simulation result of the transient response when $C$ is at $C_{\text{max}}$.

**Figure 12.** Simulation result of the transient response when $C$ is at $C_{\text{min}}$. 
5.3. Discussion

As the results indicated, there are discrepancies between the simulation and the experiment results. This is due to the manufacturing tolerances, the fringe capacitance, and the system parasitic capacitance. The fringe effect is caused by the sharp edges of the multipole variable capacitor plates, which cause bending of the electric field lines at the edges of the plates in comparison to the straight field lines inside the dielectric material (air). As a result, the flux is not properly linked with the second plate as it is moving in rotational motion, which leads to an additional fringe capacitance parallel to the variable capacitor [21]. The parasitic capacitor is an additional capacitance formed between the capacitor poles and any nearby conductors [22]. This causes a considerable increase in the capacitance value at different angular positions [2,3].

For the presented model, the parasitic capacitance was formed due to two reasons. First, the capacitor
during measurement was not properly isolated from the physical surroundings. Second, the test leads of the GW Instek 816 LCR meter added parasitic capacitance. Although it had shielded cables, it had a capacitance of around 30 pF.

To ensure that the performance of the tested prototype was acceptable, the capacitor model was compared with five different types of variable capacitors used for energy harvesting from previous studies. The result of the comparison was found to be consistent, indicating that the variable capacitor performance was satisfactory in terms of capacitance variation and the maximum energy which could be harvested. A summary of the results is given in the Table below.

<table>
<thead>
<tr>
<th>Harvester type</th>
<th>$C_{\text{max}}$–$C_{\text{min}}$</th>
<th>Power/energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive harvester [23]</td>
<td>200–100 pF</td>
<td>350 nW</td>
</tr>
<tr>
<td>Rolling rod harvester [25]</td>
<td>10–2 pF</td>
<td>2.4 mW</td>
</tr>
<tr>
<td>VC machine generator [3]</td>
<td>40–9 pF</td>
<td>100 μW</td>
</tr>
<tr>
<td>CYTOP electret generator [26]</td>
<td>25.4–39.8 pF</td>
<td>6.4 μW</td>
</tr>
<tr>
<td>Multipole capacitor harvester</td>
<td>110–39 pF</td>
<td>76.61 mW</td>
</tr>
</tbody>
</table>

6. Conclusion
This research provides an inclusive study of a variable capacitor specifically used for electrostatic wind energy harvesters. The multipole capacitor can be attached to a gear box and a micro-wind turbine to convert mechanical energy to electrical energy. A prototype of the variable capacitor was simulated and tested. An AutoCAD model was used to calculate the effective area between the stator and the rotor. After that, the total capacitance variation with angular position was determined using MATLAB. Simulation results show a capacitance variation between 83 pF and 0 pF. The transient response test shows that the settling time for the capacitor at maximum is 5.5 μs and at minimum it is 2 μs. The experimental measurements show that the capacitance of the device varies from 110 pF to 39 pF. The transient response test shows that the settling time for the capacitor at maximum is 8.8 μs and at minimum is 5.5 μs. The difference between the values measured in the simulation and the experiment can be reduced if a better prototype is constructed and better isolation is provided while testing. However, differences cannot be completely avoided due to the existence of fringe and parasitic capacitance in the system. Results from the theoretical torque analysis indicate that in order to rotate the rotor of the capacitor, it is necessary for the torque $T_T$ to be greater than $(n_1/n_2)T_C$.

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References


