Modeling of Low Power Electrostatic Wind Energy Harvester for Macro-Scale Applications

R. T. Abdulmunam, L. Y. Taha, and P. C. Ivey,

Abstract—**The aim of this paper is to investigate the performance of a new macro scale electrostatic harvester model linked to a micro wind turbine. The harvester consists of a multi-poles rotary capacitor and a converter circuit. First, the model of the harvester is implemented in Matlab/Simulink. Next, the validated model device parameters such as the passive elements and the battery capacitance are varied to extract the optimal harvested power. Results indicate that maximum harvested power is 4.76 mW at a wind speed of 10 m/s with harvested energy of 219 µJ per cycle.**

Index Terms—**Electrostatic harvester, energy harvesting, variable capacitor, wind energy.**

I. Introduction

The utilization of wind energy has a very long history to over 3000 years ago [1]-[3]. Wind energy is a clean, inexhaustible and sustainable source of energy [1], [2]. The development of wind energy harvesting technology has been moving very fast in many new dimensions. The main trend of wind turbine development is large scale wind turbine with conventional generation systems that are regularly established on vast wind sites were average wind speed is high [3], [4]. On the other hand, in regions of low wind speed and in crowded areas, micro wind turbines are more suitable [3]. This type of wind turbine has received attention in recent years and a great deal of research has been conducted to reduce its cost and increase the generated output power [3].

The cost of micro wind turbine system operating with conventional generators could be reduced by the direct generation of DC power using electrostatic generators [5]. Although the power density of the electrostatic generators is less than that of the electromagnetic conventional generators, variable capacitor in electrostatic harvester could lead to a system of equitable power density to an electromagnetic generator-transformer-rectifier combination with the expected reduction in component count reducing system cost and increasing the overall efficiency [5], [6].

Fig.1 shows schematically (a) a conventional generator system (b) an electrostatic generator system. Previous researches show that the electrostatic generator can be considered as a new technology for the direct generation of DC power; moreover, it has a number of merits for more efficient power generation [5]-[7]. Various electrostatic realizations methods were reported in previous studies such in-plane overlap, in-plane gap closing converter and out-of-plane gap closing converter [7]-[19]. In most of these researches the source of energy used is the vibration energy; Furthermore, the motion mechanism is linear. Roundy et. al reported a gap closing capacitor that can be used to harvest optimal output power of 100 µW [9]. Despesse et al presented an in-plane gap closing device that was designed to utilize vibrations at low frequencies to generate 1052 µW of power at 50 Hz [19]. Mitcheson et al developed a non-resonant electrostatic generator that consists of a silicon proof mass and it required a 100 V input to produce 3.7 µW of power [18]. No previous work was reported in using the wind energy with electrostatic harvester for low power applications, specifically a rotary capacitor based harvester. Thus investigations are required.

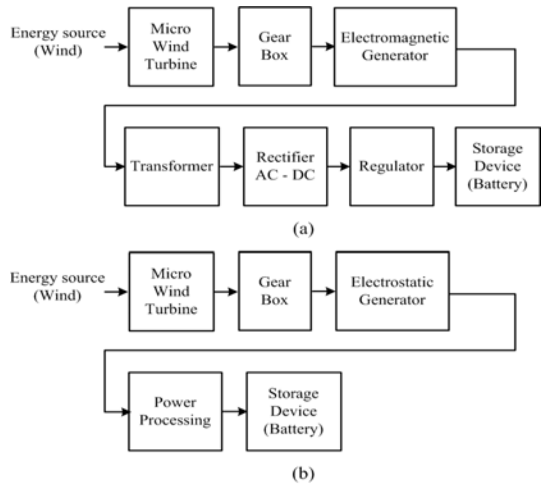

Fig. 1. Wind energy generation system concepts. (a) Conventional generator system (b) Proposed electrostatic generator system.

The aim of this paper is to investigate the performance of a specially designed macro scale electrostatic energy harvester that is linked to micro wind turbine and a rotary variable capacitor. The validated model device parameters such as the inductor, the harvesting diode type, the input voltage and the battery capacitance are varied to extract the optimal harvested power.

II. Electrostatic Energy Harvester Profile

The electrostatic energy harvesting approach uses the change in capacitance to either cause a voltage increase in a constant charge system, or a charge increase in a constant voltage system [9], [20],[21]. The total charge Q of the

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capacitor is worked out by multiplying the voltage V with the capacitance C as in (1):

$$Q = CV \tag{1}$$

By fixing both the voltage and the charge and then varying the capacitance, the unfixed part must change itself to suit the basic equation. Energy E can then be calculated using (2) as follows [22]:

$$E = \frac{1}{2}CV^2 \tag{2}$$

A capacitance decrease forces the unfixed element of Q to decrease or the unfixed element of V to increase. Energy is required to lower the capacitance, and this energy can then be expressed in the increase in total energy of the capacitor [22]. As declared in I different types of electrostatic capacitors were studied such in-plane overlap, in-plane gap closing converter and out-of-plane gap closing converter. The variation of the these capacitors relies on modifying either Area of the capacitor plates A, the distance between them d or the dielectric constant of the insulation material between the plates ε based on the capacitor equation[21],[221]:

$$C = \varepsilon_o \varepsilon_r \frac{A}{\mathrm{d}} \tag{3}$$

As an alternative, the work presented in this paper introduces another type of electrostatic harvester that relies on modifying the area in a rotary integrated multi pole variable capacitor as shown in Fig. 2.

III. Proposed Electrostatic Energy Harvesting Model

Fig. 3 illustrates the proposed electrostatic energy harvester model. Details of the model parts will be discussed in section A and B.

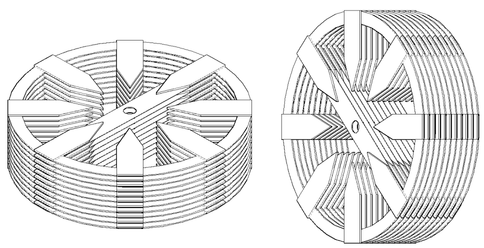


Fig. 2. Multi pole variable capacitor

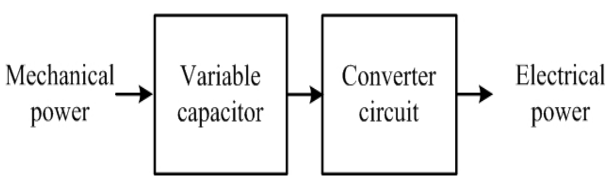


Fig. 3. Electrostatic energy harvester

A. The Variable Capacitor

A multiple poles rotary type variable capacitor is used in this work. This construction has many advantages such as providing higher amounts of power, higher capacitance variations, and less fringing [5], [6]. The multiple pole capacitors have a number of parallel plates separated by air as the dielectric material. Each capacitor plate can produce a specific amount of power during energy harvesting. The number of plates is proportional to the amount of harvested power. When number of poles is increased, it increases the speed of capacitance variation. As a result, number of harvesting times per cycle increases [5], [8].

Most capacitors depend on two important geometric factors, area of the plates or the distance between the plates. However, this variable capacitor depends only on the variation of plate area with time. The area of the capacitor plates is a critical parameter for the computation of the minimum and maximum capacitance and it has strong relationship with amount of harvested power [5].

B. The Electrostatic Converter Circuit

A number of basic architecture circuits for electrostatic converters are reported in literature [23]-[29]. All these architectures fall into two main approaches: the charge pump and the switched inductor approach. In the charge pump approach an energy loss occurs if two capacitors with different initial energy are connected [30]. In the switched inductor approach the inductor converters are capable of producing high energy gains when supplied from low power kinetic energy sources [31].

A comparative assessment was carried out in this paper to test various approaches of designing the circuit then addressing the optimum harvested energy. Results indicate that optimum energy can be extracted using the circuit shown in Fig. 4. The proposed converter circuit consists of two switches, an inductor, a harvesting diode and the variable capacitor. Since the inductor is a quasi lossless device [10], it is used to transfer energy from the battery to the variable capacitor. A diode, on the other hand, naturally allows the current to pass in one direction towards the battery, so it only dissipates ohmic losses. Considering the low power losses, risk and complexity of other types of semiconductor switches, the diode appeals to be more suitable for this circuit [10]. The converter operation cycle consists of two steps. First, by closing switch 1, energy is transferred from the battery to the variable capacitor through the inductor. Second, by closing switch 2, the energy stored in the capacitor is transferred back to the battery through the diode.

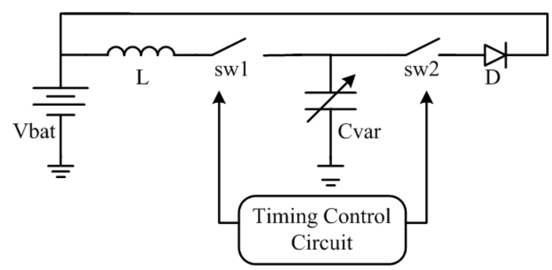


Fig. 4. The proposed electrostatic converter circuit

The operation cycle of the converter is controlled by the timing control circuit. The timing control circuit is activated when wind energy is applied to the harvester. The charging through sw1 starts when the capacitance reaches its maximum value. Additional charge will be stored in the capacitor. When the capacitance is at its minimum value, the initial energy and the additional energy is transferred back to the battery through sw2 and the diode.

IV. Simulation Model

The converter circuit is implemented in Simulink as illustrated in Fig. 5. In response to the applied mechanical motion, the variable capacitance will change as function of time. The capacitor in Fig. 2 is modeled by a variable capacitor C_{var} in parallel with a fixed parasitic capacitor C_{par} [10], [23]. The capacitance varies between 120 - 40 pF.

The energy transfer units consist of an inductor L and a harvesting diode D_2. The inductor is 0.01μH and has an internal resistance of 100 Ω. The diode D_2 is considered to be a germanium diode with forward voltage of 0.3 V. The battery is modeled by a capacitor C_b in series with resistor R_b, to present a Li Ion battery with voltage spans between 2.5 - 4.2 V [10], [23].

The optimization is carried out by varying the wind speed, the input voltage, the inductance, the diode type, the battery capacitance, and the load resistance. Table I shows five parameter variations used in the simulation.

V. Results and Discussion

A. Simulation Results

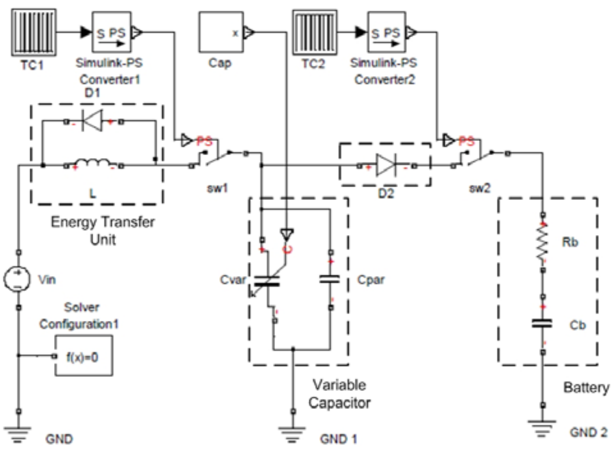


Fig. 5. The Simulink model for the electrostatic converter circuit

As previously mentioned in III, the harvester operation is activated by the timing control circuit. Fig 6 shows the timing control signals that controls sw1 and sw2. First, when sw1 is activated, the charging of the capacitor starts until it is fully charged. Next, sw1 opens and sw2 closes to transfer the charge from the capacitor back to the battery through the harvesting diode. Fig. 7 illustrates the results of charging and discharging the capacitor. The capacitor voltage increases from 0 – 2.5 V until it is completely charged then the voltage starts decreasing. However, the current starts from its maximum value of 24.6 mA and then decreases to 0 mA. Simulation test of the multi-poles variable capacitor is illustrated in Fig. 8. The timing diagram shows the capacitance variation and the capacitor voltage when windspeed of 10 m/s is applied. As the capacitance reaches maximum, the control circuit sends a signal to charge the capacitor. In Fig. 9 (a) the maximum average power generated occurs at 93.26 mW when the wind speed is 12 m/s and the input voltage is 10 V. The results indicate that more power can be harvested at higher wind speed and at higher input voltages. However, the output power is approximately the same when the input voltage is between 2.5 - 5 V for the given different wind speeds.

TABLE I: The Parameter Variations Used in Simulation

	Wind speed (m/s)	Input voltage (V)	Inductance (μH)	Diode type (Ge, Si)	Battery capacitance (F)	Load resistance (Ω)
1	2 -12	2.5-10	0.01	Ge	1	0
2	2 -12	2.5	0.01 - 100	Ge	1	0
3	2 -12	2.5	0.01	Ge, Si	1	0
4	2 -12	2.5	0.01	Ge	1n - 1	0
5	2 -12	2.5	0.01	Ge	1	0.001-10 k

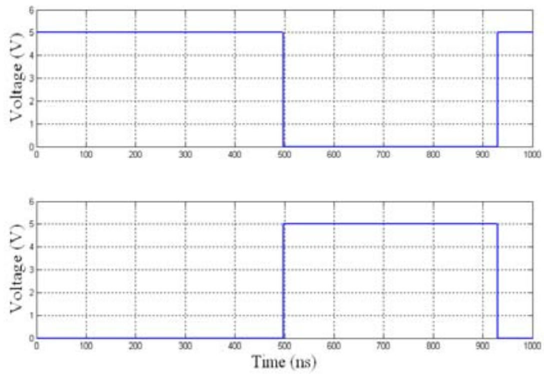


Fig. 6. The timing control signals

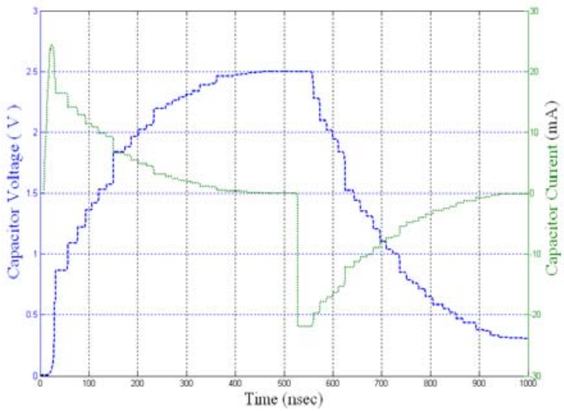


Fig. 7. The variable capacitor voltage and current

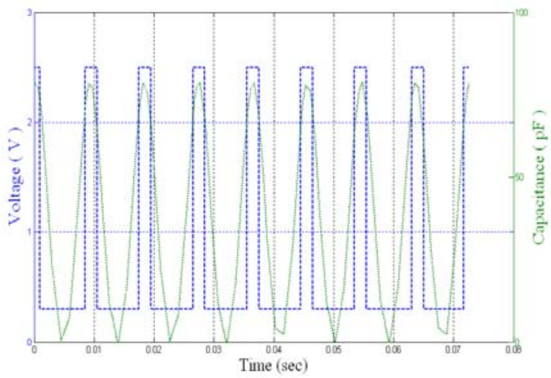
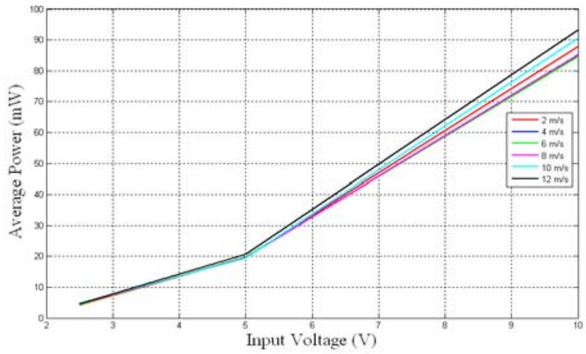
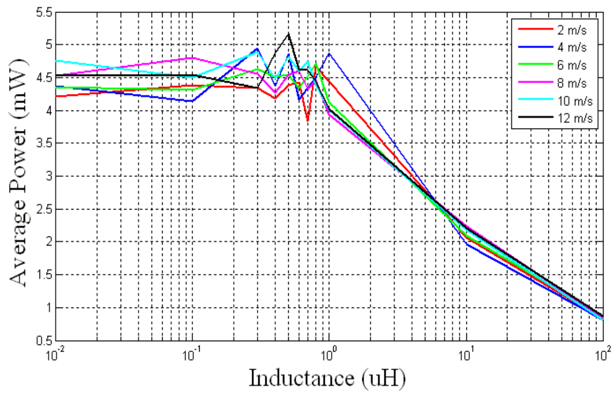


Fig. 8. The capacitance variation with time

Fig.9 (b) indicates that the power increases when the rpm increases, where the maximum output power generated is 4.79 mW at 8 m/s when 0.1 μH inductor is used in transferring energy. This suggests there will be less power harvested when using high inductor values. Fig.9 (c) illustrates the variations of the generated power with the type of harvesting diode at various wind speeds. Higher power can be produced by reducing the forward voltage of the diode which is connected in series to the battery. As a result, a germanium diode with a forward voltage of 0.3 V is more suitable for this harvester circuit. Fig.9 (d) shows the influence of the battery capacitance on the output power at wind speed of 2 -12 m/s. The suitable capacitor for this circuit is between 1mF – 1 F. Higher capacitance values give unstable output power. This instability might be due to the big difference between the capacitance of C_{var} and C_b and the low capacitance values, give a low output power. Fig. 9(e) demonstrates the effect of varying the load resistance on the generated power at various wind speed. The results shows that the maximum power generated at resistance between 0.1 -1.0 Ω.



(a)



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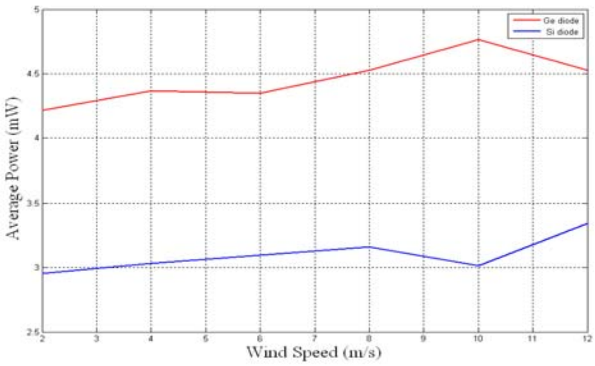

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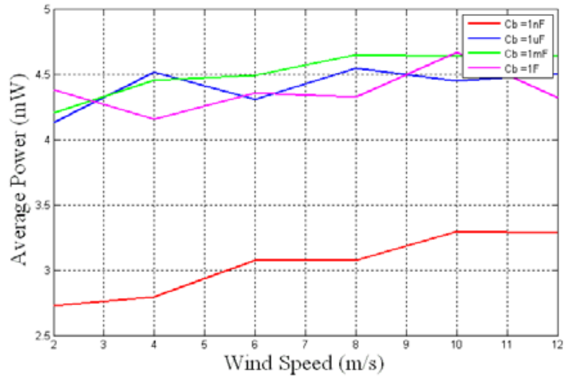
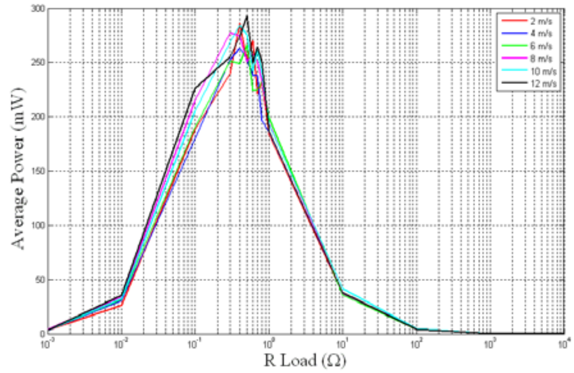


(d)



(e)

Fig. 9. Generated power under varying conditions for the harvester in Fig. 5 (a) Generated power with varying input voltage. (b) Generated power with varying inductance. (c) Generated power with two diode types. (d) Power variation with respect to wind speed at varying capacitance. (e) Power variation with respect to load resistance at varying wind speed.

TABLE II: THE POWER OUTPUT AT VARIOUS WIND SPEED

Wind speed (m/s)	Cycle time (ms)	Output power (mW)	Energy gain (μJ)
2	363.3	4.372	655.6
4	181.6	4.456	499.5
6	121.1	4.488	356.6
8	90.8	4.650	275.8
10	72.6	4.761	219.2
12	60.5	4.635	157.0

B. Optimization Results and Discussion

Table II compares the power output and energy gain for various wind speed. The harvester model was tested at L = 0.01 - 0.1 μH, Diode voltage is 0.3 V, C_b = 1 m F and V_{in} is 2.5 V. The maximum harvested energy occurs at minimum wind speed. However, maximum harvested power occurs at maximum wind speed. The energy gain given in Table II can be worked out by multiplying the instantaneous power with the time. At wind speed of 2 m/s, the energy gain is 655.6 μJ for the time period of 363.3 ms. However, at wind of 12 m/s, the energy gain is 157 μJ for cycle time of 60.5 ms. the proposed harvester can complete 1 cycle within 363.3 ms at wind speed of 2 m/s and 6 cycles at wind speed of 12 m/s. Therefore the total harvested energy at higher wind speed is more than the energy gained at low wind speed for the same indicated cycle time. Fig .10 shows the harvested power and energy gain for wind speed of 10 m/s. The figure illustrate that the energy rises with time. Over the cycle time of 72.6 ms, an average of 219.2 µJ of energy is harvested. Fig.11 presents the Simulink results on the relationship between the power output and the wind speed of the same multi-poles variable capacitor. The curve indicates that the electrical power output of the harvester increases as wind speed increases reaching its maximum at 10 m/s and then decreased thereafter. Therefore, it is better to operate the harvester at wind speed higher than 8 m/s to receive a higher power output.

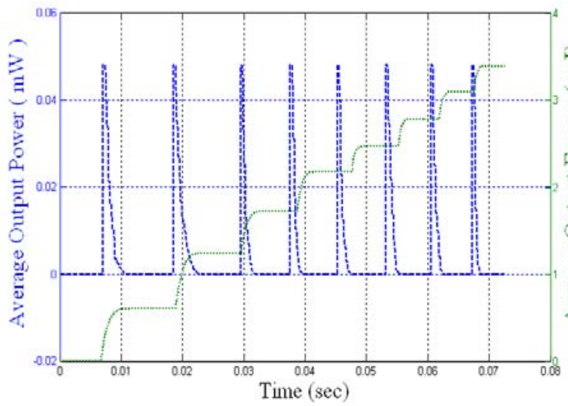


Fig. 10. Sample power output and energy gain at wind speed of 10 m/s

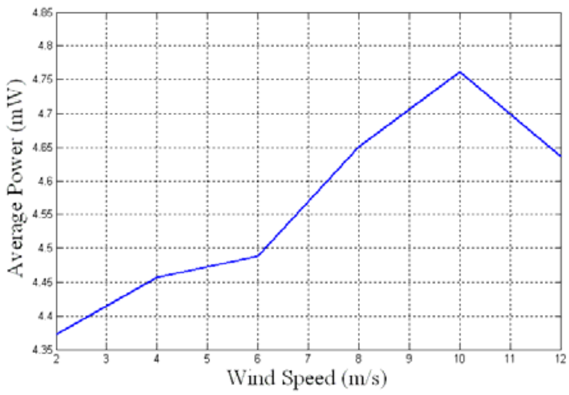


Fig. 11. Relationship between power output and wind speed

VI. Conclusion

This study investigates the variation of the performance of electrostatic wind energy harvester with different model parameters. The simulation results show that more power can be generated at higher wind speed, higher battery capacitance values and lower inductance at the transfer circuit. This is certainly necessary for the achievement of high energy gain. The proposed harvester requires wind speed of 10 m/s to give power output of 4.76 mW and energy gain of 219.2 µJ within a time period of 72.6 ms. Load resistance tests on the harvester proved that the harvester is operational in a wide resistance range and a high output can be generated at load resistance between 0.1 – 1 Ω. Although the variable capacitor is the key element of the harvester, a complete harvester will require suitable power processing circuits. The overall efficiency of the energy harvester system will depend on the related electronics, power processing circuit as well as the efficiency of the mechanical capturing device which is represented by the micro wind turbine. The design of such harvester has been outlined, and the implementation of the prototype is currently under way. The proto type will be used to provide experimental validation of the simulation results that need to be studies and understood in a more fundamental way.

Acknowledgment

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