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Innovative Method of Non-Contact Electric Field Energy Harvesting Under 275kV Power Transmission Line

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Abstract

Advance technologies in today's world gradually developing and bringing many innovative products and findings. One of the improving technologies of all time are energy harvesting. With a massive amount of external sources, energy harvesting can be a prominent and alternative solution to provide power supply without batteries in a more cost effective at the same time environment friendly way. In this paper, a new method of harvesting electric field under 275kV transmission line is applied by using innovative design of non-contact electric field energy harvester (EFEH). Seven significant design parameters such as the capacitance of the harvester, the material and thickness of harvester and the surface nature of the harvester are examined and improved step by step ensuring an efficient, cost effective and less complaicated EFEH design. ANSYS Maxwell software is used to simulate, analyse and compare the electric field captured on each designs. In order to support the electric field simulations of all the harvester designs, EFEH prototypes are built and tested under a 275kV electrical transmission lines surroundings. A maximum of 14.5V of AC voltage from the harvester and

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7uW of output power is recorded from the most efficient EFEH design using a simple half wave rectifier 10uF capacitor in filter. The proposed EFEH can be implemented to energize low powered sensors that are used to monitor conditions of electrical transmission lines and the vicinity surrounding the tower especially in areas that cannot be easily accessed by people.

Keywords: Power transmission line, Capacitance, Electric field, Electric field energy harvesting, Non-contact.

1 Introduction

The Electric field energy harvesting method is considered as one of the most reliable and preferred technique to be used to energize power line transmission systems condition monitoring sensors such as tilt, vibration and stay sensors as the surroundings has an abundant amount of electric field even in an open circuit state. Power that comes from solar, thermal, radio frequency and vibration to energy are typically limited in rural areas where most of the power transmission lines existed [1]. Even though electric field energy harvesting method is proven as an effective way to harvest energy, there are still technical challenges as previous studies show that existing EFEH are designed in such a way that it is either clamped around the line [2]–[6] or attached directly [7]–[10] to the power transmission line which makes the installation of the prototypes complicated and tedious.

Limited studies were done by modifying or improving the EFEH designs in order to avoid the stated complications and challenges. According to the model in [11], it has been proven that a non-contact EFEH is possible to be designed without being attached to the power lines. This harvester could harvest up to 4V of AC voltage under a 765kV power line without in contact with the line at 4 meter distance from ground. However, no past literature has attempted to modify and improve the EFEH designs. In this paper, a basic non-contact EFEH is designed and its structure and materials were modified with respect to seven design parameters. By performing these specific modifications, this research aims to design a harvester that can harvest more AC voltage from stray electric field of power transmission line than the previous studies.

Section 2 explains the materials and methods on variating the EFEH design parameters and procedures for the actual setup as a prove of effectiveness of EFEH. Section 3 of the paper describes and demonstates the electric field simulations obtained and the actual results from the fabricated prototype as a validation of the EFEH design. The conclusion and the future works are discussed in Section 4.

2 Materials and Methods

This research aims to harvest the maximum amount of AC voltage from stray electric fields irradiating from 275kV transmission lines and convert it to usable power for low powered sensors. Parameters shown in Table 1 are possible designs considerations for EFEH. Each parameter is varied for each EFEH design as shown in Fig. 1 via the ANSYS Maxwell software..

As the first step of designing EFEH, the shape of the harvester is studied. Existing EFEH are either hollow cylinders or parallel square plates [1]. Hollow cylindrical shaped capacitor are mostly used in [2], [3], [6] and in harvesters that are conditioned to be looped around the line. The harvester's hollowed structure can be easily used to clamp around a straight cylindrical power line compared to any other shapes. Square parallel plates is also another harvester shape that are used in [7]–[9], [12]. Both these shapes are designed and simulated in ANSYS Maxwell to compare the electric field captured around the shapes since the EFEH will be tested without contact with the line.

All the designs of the EFEH is constructed and drawn 3 meters from the ground as shown in Fig. 2. A colour map with a descending range of electric fields is displayed on the simulation to measure the amount of electric field captured on each design. The electric field captured in all the simulation are assumed to be slightly higher compared to actual testing results as the environmental factors and other resistance such as the power line phasing and ground resistivity are not considered.

Table 1 Variable parameters and the respective symbols

Parameters	Symbols
The shape of harvester	S
The position of harvester	P
The air gap of harvester	G
The material and thickness of harvester	M
The dielectric material of harvester	D
The surface area of the harvester	A
The surface type of harvester	T

Both the parallel plates and the hollow cylindrical capacitors use aluminium foil as the material. A minimized and compact surface area of 462cm^2 is maintained equally for both shapes. The spacing for the parallel plates is also fixed at 1.5cm.

The graphs in Fig. 3 shows patterns for typical and maximum electric field values when the distances are varied horizontally, measured beneath double circuit overhead lines.

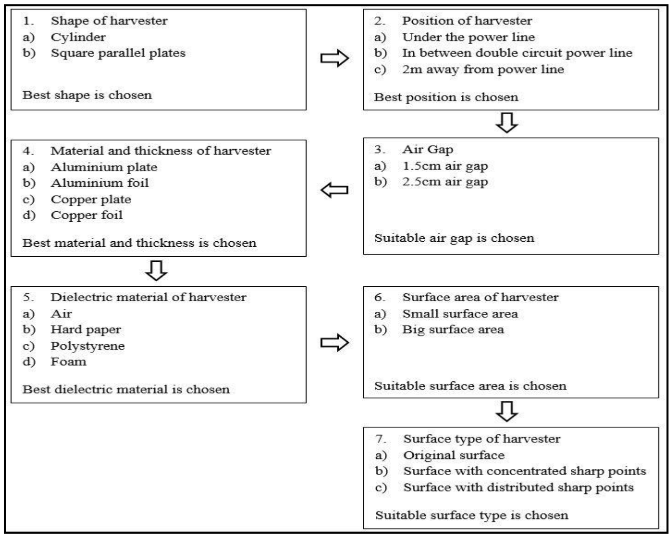


Figure 1 The stages of forming an efficient EFEH

The electric field is found highest exactly under both the power lines and almost 0 kV/m in between the power lines and reduced when the distance is furthered horizontally away from the line.

To prove the effect of position of harvester to the electric field captured, a comparison is done with the reference plate's position as shown in Fig. 2 and parallel plates being placed in between lines and 2 meters horizontally away from line.

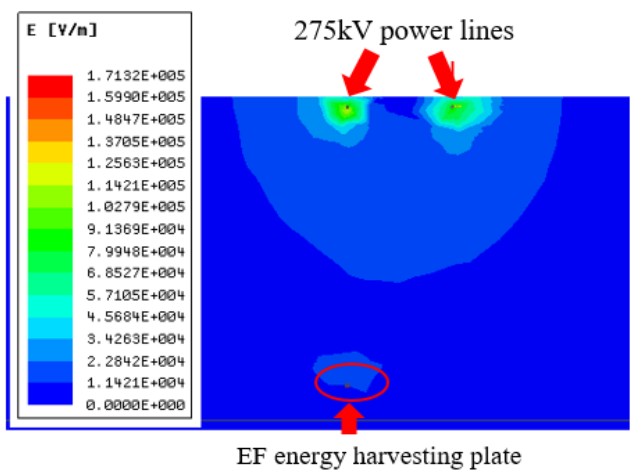


Figure 2 Simulation of electric field generated around 275kV power line using ANSYS Maxwell software

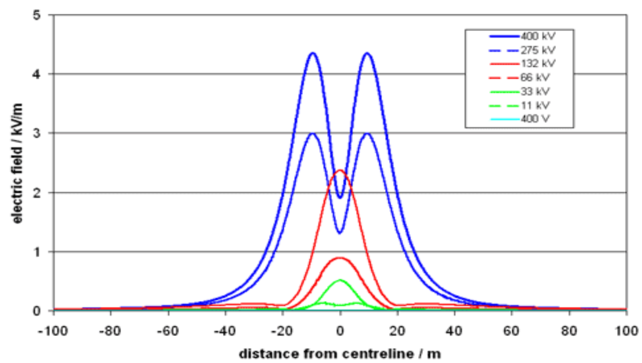


Figure 3 Regular range of for power transmission line with different voltages [13].

The basic capacitance formula of a flat, square parallel plate is given as shown in (1) where constant, ε is the permittivity of space which equals to $8.85\times10-12$ F/m . The formula is only relevant when the distance between the capacitor's plates smaller than the width of the plates [9]. The energy stored in a capacitor can be increased when the capacitance is increased [14]. The capacitance of the plate is influenced by the gap or spacing between plates, G, dielectric material's permittivity, D and also the surface area of the plate, A [15].

$$\frac{\varepsilon.D.A}{G} \quad (1)$$

Greater capacitance is achieved when the plates are kept closer as it increases both the electric field force and field between plates. The suitable air gap is identified after choosing the shape and the position of harvester to keep the spacing fixed in the next parameters testing. The EFEH harvester simulation is varied where the reference parallel plate with 1.5cm spacing is compared with another parallel plate with a 2.5cm spacing.

Material and the thickness of the conductive parallel plates are also considered as parameters that can affect the electric field flow. Copper and aluminium are commonly used as material to design harvesters as both have high electrical conductivity. In terms of thickness, both the materials are varied in form of solid plate or in form of foil. Studies shows that aluminium foil is the most preferable material and thickness to be used as harvester made from aluminium foil is not only lighter, cheaper and user-friendly but it also could capture electric field almost similar to the electric field captured using solid plate, which is much heavier and not cost effective [4], [10], [11], [16].

Table 2 Relative permittivity of dielectric material used [17]

Dielectric Material	Relative permittivity
Air	1.006
Hard paper	1.5-2
Polystyrene	2.4-2.7
Foam	2.8-3

All other factors being equal, higher relative permittivity of the dielectric material and bigger surface area will also increase the capacitance of parallel plate harvesters. Before performing the next design parameter simulation, the suitable dielectric material is chosen. Air, hard paper, polystyrene and foam are the four types of easily found dielectric materials used to vary the EFEH design where Table 2 shows the relative permittivity of each material ordered from lowest to the highest relative permittivity. On the other hand, surface area of the plates with foam is then compared by doubling the length and the width of the plates.

Finally, an investigation is made by modifying the surface's nature of the EFEH from a smooth and even surface to a surface with distributed sharp points and concentrated sharp points. Studies show sharper shapes will gather and harvest greater electric charges compared to the usual square shaped plate.

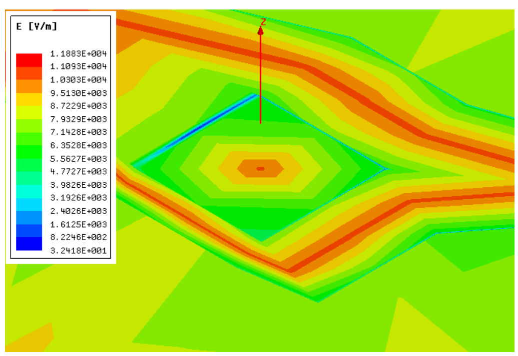
In order to support the simulation resuls, EFEH is designed and the actual setup under a 275kV transmission line is arranged as shown in Fig. 4 where the plates are kept at the height of 3 meters from the ground with reference to a safe clearance level. Referring to Table 3 in [1], the average electric field intensity measured by extra field metres is ranged from 5.8kV/m to 6kV/m. The design of the harvesting plate is varied according to Table 1. Each design's maximum AC voltage and current captured are recorded. All testing was performed for two consecutive days and the measurements were taken every 10 seconds. AC voltage harvested was rectified using a simple half-wave rectifier and the maximum output power from a 220kOhm resistor was also recorded every 10 seconds.

Figure 4 Actual setup under 275kV transmission line.

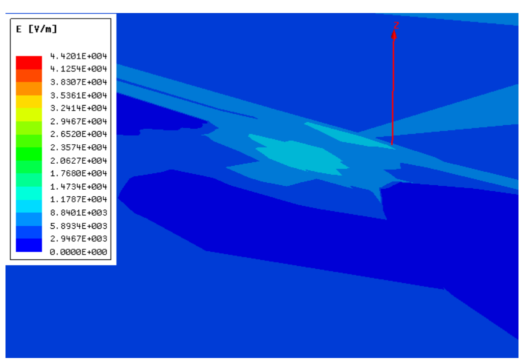
3 Results and Discussion

Simulation is performed where the varied harvesters are tested one at time to observe performance improvements and electric field captured. Firsly, the electric field simulation of EFEH with respect to shape of harvested is investigated.

Fig. 5(a) shows the electric field captured around the parallel plate harvester while Fig. 3(b) shows the electric field captured around the hollow cylindrical harvester. The parallel plate harvester captured a maximum of 11.89kV/m while hollow the cylindrical capacitor captured a maximum of 8.84kV/m of electric field. This evidently shows that, with the same surface area, the parallel plate harvester could harvest more electric field compared to the hollow cylindrical capacitors. Though hollow cylindrical capacitors are commonly used as an EFEH shape, its curved structure is not suitable to be used as a non-contact harvester. Hence, a parallel plate shaped harvester as shown in Fig. 6 is used as the reference shape for the following design parameters simulation.



(a)



(b)

Figure 5 (a) Electric field simulation of parallel plate's harvester; **(b)** Electric field simulation of hollow cylindrical harvester.

For the position of harvester design parameter, a maximum of [18] 10kV/m of electric field in between lines and 6kV/m for 2 meters away from the lines are captured in simulation where the results clearly verified that the harvester is best positioned directly under any of the power lines, provided both the lines are assumed to produce equal amount of electric fields.

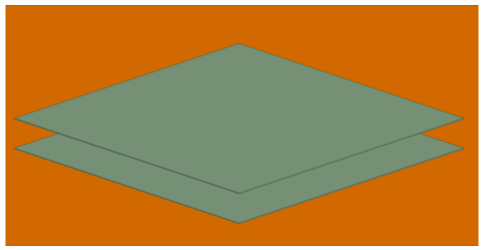


Figure 6 Parallel plate with 1.5cm spacing

Subsequently, the harvester with 2.5cm air gap captured a maximum electric field of 4.59kV/m as shown in Fig. 7, thus proving that parallel plates with 1.5cm spacing captures more electric field.

The simulation variation is also performed to test the effect of material and thickness design parameter and the results proves that aluminium foil can harvest higher amount of electric field compared to copper foil, copper plate and aluminium plate.

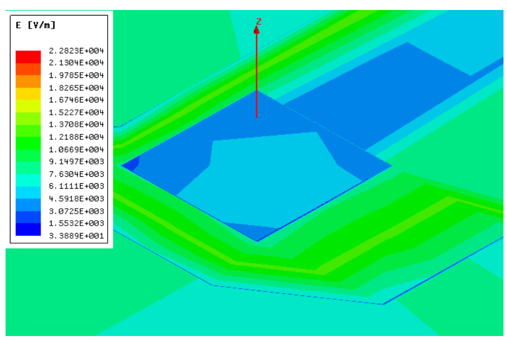


Figure 7 Electric field simulation of parallel plates with 2.5cm of air gap.

From the simulation results with respect to dielctric materials shown in Table 2, hard paper, polystyrene and foam captured equal amount of electric field which is around 12.7kV/m as shown in Fig. 8 as the relative permittivity is higher compared to air. A validation is made by setting up the prototype harvesters with all types of dielectric under 275kV power transmission line to get a better result to compare with. For now, foam is chosen for the next parameter simulations as is has the highest relative permittivity of all the dielectrics used.

Simulation of surface area as shown in Fig. 9 proved that bigger surface area captured an electric field of 13.65kV/m which is 7.5 % higher than the plates with smaller surface area.

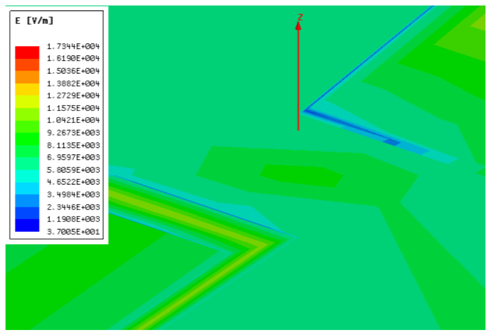


Figure 8 Electric field simulation of parallel plates with foam, polystyrene and hard paper as dielectric material.

Table 4 shows the measured maximum AC voltage, maximum current and maximum output power captured and harvested from variety of actual EFEH harvesters. The maximum output power harvested increased as expected when the design parameter is varied with respect to the law of capacitance. A maximum of 7.007uW of power or 7.007J/s of energy is constantly harvested from the final design which proves the simulation that a 1824cm^2 aluminium foil parallel plates with 1.5cm of foam space can harvest the highest electric field without in contact with the transmission line.

Table 3 Summary of maximum electric field captured via simulation

Testing Parameter (Symbols)	Harvester Designs	Maximum Electric Field On Plate (kV/m)	Chosen Harvester
S	Cylinder	8.84	
	Parallel Plate	10.29	✓
P	Between the Lines	6.11	
	2m away from Line	5.48	
	Under the Line	10.29	✓
G	2.5cm	10.29	
	1.5cm	11.89	✓
M	Copper Plate	6.51	

	Aluminium Plate	6.51	
	Copper Foil	11.86	
	Aluminium Foil	11.89	✓
D	Air	11.89	
	Paper	12.73	
	Polystyrene	12.73	
	Foam	12.73	✓
A	Small	12.73	
	Big	13.63	✓
T	Plate with distributed sharp points	10.92	
	Plate with concentrated sharp points	13.94	
	Plate without sharp points	13.63	✓

Changing the design parameters one at a time has proved that there is a drastic increase in the electric field captured on the EFEH. From the summary on Table 3, the most electric field is captured on 1824cm^2 aluminium foil parallel plates with 1.5cm of foam space placed directly beneath a 275kV electrical transmission line. Electric field captured has been improved from the lowest of 5.48kV/m to the highest of 13.63kV/m making the designed harvester to be 148% more efficient.

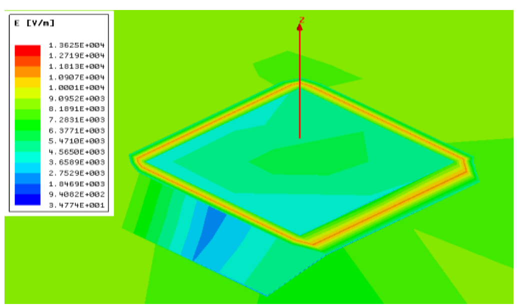
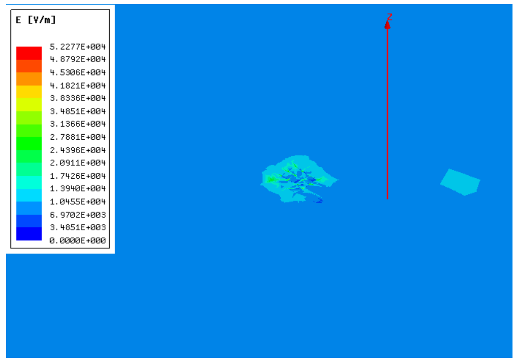


Figure 9 Electric field simulation of bigger surface area parallel plates with foam as Dielectric Material

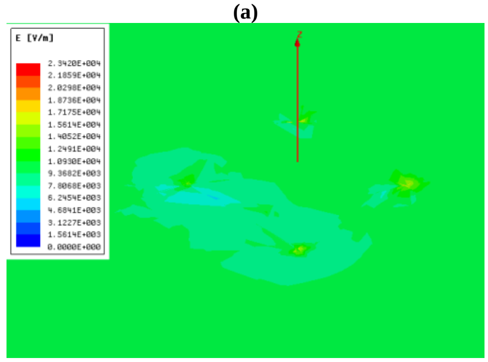
Table 4 Summary of the performances of harvester designs.

Testing Parameter (Symbols)	Harvester Designs	Max AC Voltage (V)	Max Current (mA)	Max Output Power (uW)
S	Cylinder	1.06	0.0935	0.06065
	Parallel Plate	1.31	0.2385	0.1676
P	Between the Lines	1.385	0.0215	0
	2m away from Line	0.58	0.105	0
	Under the Line	1.31	0.2385	0.1676
G	2.5cm spacing	1.31	0.2385	0.1676
	1.5cm spacing	5.8185	0.112	0.3597
M	Copper Plate	3.855	0.0625	0.0663
	Aluminium Plate	5.18	0.079	0.0374
	Copper Foil	4.43	0.076	0.11415
	Aluminium Foil	5.8185	0.112	0.3597
D	Air	5.8185	0.112	0.3597
	Paper	4.605	0.2725	0.46035
	Polystyrene	6.0675	0.401	0.2486
	Foam	5.585	0.486	2.88425
A	Small	5.585	0.486	2.88425
	Big	14.525	0.3595	7.077
T	Plate with distributed sharp points	10.15	0.3945	6.32845
	Plate with concentrated sharp points	6.81	0.227	2.23675
	Plate without sharp points	14.525	0.3595	7.077

Figure 10 shows (a) Electric field simulation of parallel plate's harvester with concentred sharp points; (b) Electric field simulation of parallel plate's harvester with distributed sharp points.



(a)



(b)

Figure 10 (a) Electric field simulation of parallel plate's harvester with concentred sharp points; **(b)** Electric field simulation of parallel plate's harvester with distributed sharp points.

4 Conclusion

From this research, it is proven that electric field energy harvesting method is a very promising method to be used especially in rural and remote environments. For the first time, a foamed spaced parallel plate non-contact EFEH design is presented. A 220kOhm resistive load is successfully energized with a continuous maximum output power of 7.007uW. For future enhancements, an improved rectification and power conversion circuit can be designed to get sufficient and better amount of power. In this paper, a non-contact, reliable, inexpensive and field-proven EFEH was simulated and tested. As a result, it is believed that the EFEH can be widely used to energize low powered sensors for monitoring power transmission line systems as the harvester installation is easier compared to cylindrical harvesters.

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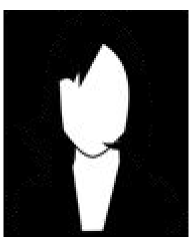
Biographies



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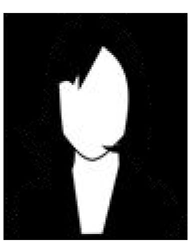

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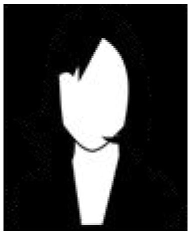

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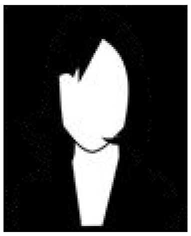

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