Characterization of Fringing Electric Field Soil Moisture Sensor to Measure Volumetric Water Content (VWC)

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***Abstract*— This paper aims to research and analyze design of fringing electric field (FEF) soil moisture sensor. Fringing electric field (FEF) sensors are usually used to detect the presence of a material or estimate the concentration of a material. Regarding to their principle, fringing electric field (FEF) sensors can be used as a tool in agriculture field to monitor volumetric water content (VWC) of soil. There are no standard analytical models for FEF sensors. The design parameters such as sensor geometry affect the performance of fringing electric field (FEF) sensors. This paper concentrate to the effect of the electrode width, number of electrode and whether there have or no ground. The FEF sensors are simulated using Finite Element Method Magnetic (FEMM). Based from the simulation results, selected design of the FEF soil moisture sensors have been fabricated using printed circuit board, PCB technology. The test is done by measure the capacitance value using LCR meter. Test results obtained are then compared with FEMM simulations. The comparison proves that the addition of shielding electrodes and ground electrode at the backplane can improve the penetration depth of FEF sensors. The increasing number electrode, small gaps between electrodes and small electrode width make the sensor more sensitive to presence moisture.**

Keywords- fringing electric field (FEF); volumetric water content (VWC); Finite Element Method Magnetic (FEMM);

I. INTRODUCTION

Volumetric water content VWC is a numerical measure of soil moisture. Soil moisture is water stored in the upper soil layer. It is simply the ratio of water volume to soil volume [1, 10]. Soil moisture is complicated to define because it means different things in different disciplines. A farmer's concept of soil moisture is different from that of a weather forecaster or a water resource manager. However, soil moisture is the quantity of water that is held in the spaces between soil particles. Another similarly applicable measurement is gravimetric water content (GWC), which measures weight rather than volume [1, 10].

Soil moisture can be determined by fringing electric field principle. Fringing electric field (FEF) sensors are normally used for non-destructive measurements of material properties, such as hardness, temperature, and viscosity [2, 6, 9]. The performance of Fringing Electric Field (FEF) sensors is evaluated based on their signal strength, penetration depth, linearity and measurement sensitivity [2, 6]. The geometry design of sensor influences the performance of FEF sensor [4, 5]. Therefore the sensor geometry chosen based from the requirement of an application [4]. Design variables include the choice of materials for electrode and substrate, the geometry of electrodes and substrate, the number of electrodes, and the arrangement of guard electrodes. The optimization process can be done either numerical simulations or analytical method [2, 6]. Although a lot factor can be design variable, this paper concentrate on electrode width, number of electrode, arrangement and number of ground electrode that affect the performance of the sensor.

Besides fringing electric field (FEF) principle, measurement of volumetric water content (VWC) or moisture in soil can also use solid-state electrical resistance as sensing device that is used to measure soil water tension. The resistance changes when the tension changes with water content [8]. The relative indication of the soil moisture level can observe because soil water is act as an electrical conductor. Once the soil dries, water is removed from the sensor and the measurement of resistance is increases. While the resistance is lowers when the soil is rewetted [8].

Monitor the content of moisture in soil are important to the land activity especially gardener. This research is toward developing a management tool for agriculture to monitor moisture content in soil. The sensor is useful help the farmer to monitoring soil moisture, and then provides efficient management in agriculture [7, 10]. The moisture level important to be controlled and maintained to prevent the inefficiently in manage on the irrigation systems. The farmers able to use smaller amount water to grow a crop, they also are able to increase yields and the quality of the harvest by using better management system of soil moisture. Besides agriculture, the sensor can be apply to other field such as Golf courses using sensors to increase the efficiencies of on the irrigation systems to prevent over-watering.

Measurement and controlling of moisture in soil needs some device that has high sensitivity and linear response to the moisture. The device in the market nowadays is expensive. All devices that have high sensitivity and accurate measurement can be categorized the good device. Low cost development may give advantage to the device to be commercialized. The main objectives of this project consist of 3 goals to achieve which are first is to investigate the development of efficient and a low cost soil moisture sensor. Then second is to study the characteristic of fringing electric field principle in designing soil moisture sensor. Lastly to design soil moisture sensor that has a higher sensitivity and accuracy also lower development cost that other models.

II. THEORY

The fringing electric field FEF sensor can be visualized as capacitor plate where moisture acts as dielectric constant. The dielectric constant is directly proportional to the moisture content [6, 9]. The moisture content is measured by take the capacitance value. Though the capacitance value, the volumetric water content, VWC in soil can be determined. In theory the formula of capacitance are as:

$$C = \frac{\varepsilon A}{d}$$

Equation 1

Where C is the capacitance in farads, ε is the permittivity of dielectric (absolute, not relative), A is the area of plate overlap in square meters and d is the distance between plates in meters

Regarding to the formula capacitance value is increases whenever the dielectric constant is increasing. This theory can happen as long as area of plate and the gap between electrodes does not change. A capacitor is a passive two-terminal electrical component used to store energy in an electric field. Once a voltage is applied across the two plates of a capacitor, a concentrated field flux is created between them that are generated by charges. The disturbance on the electric field depends on dielectric constant. More dielectric constant gives more disturbances to electric field. The disturbances on electric field give difference result on capacitance value.

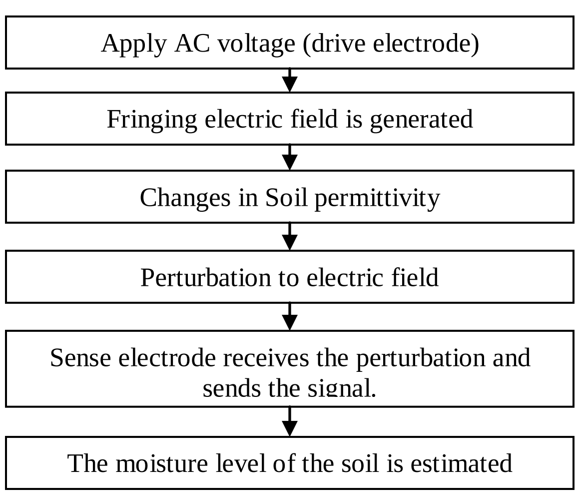

Figure 1. Principle of FEF Sensors [6]

The electric fields from the drive electrode penetrate through the sample and then terminate on the sense electrodes. The drive electrode is driven by a sinusoidal signal. The penetration depth is depending on the electrodes width and gaps between electrodes.

III. METHODOLOGY

There several methods that has been use in this project. The project methodology is explained about all the work and process that had been done toward completed the project.

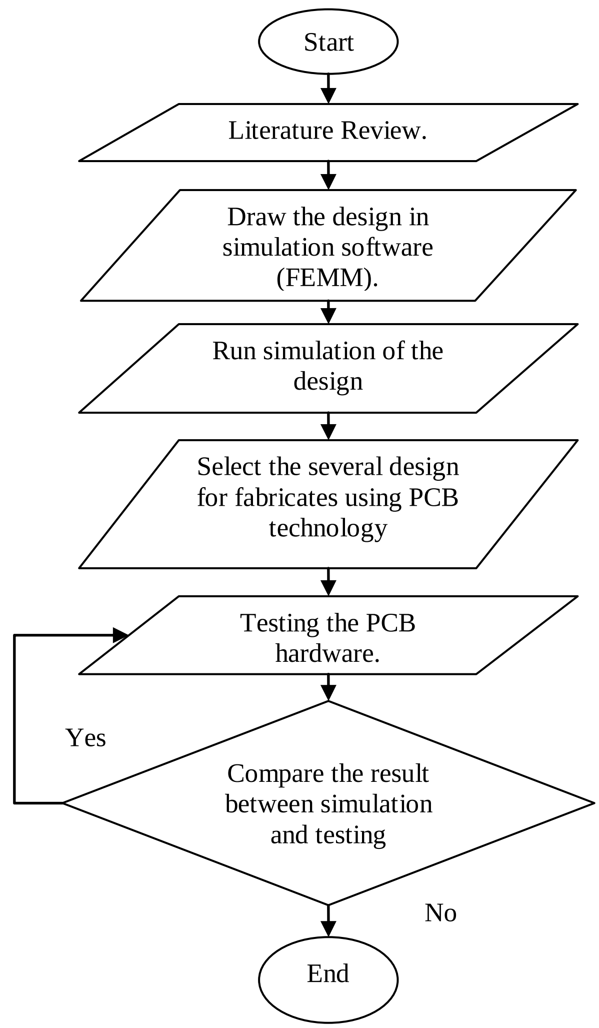

Figure 2. Flow Chart

Literature Review

The process where gather all related information about moisture sensor. The information may have in media electronic such as e-journal or e-article on the internet. The book at library may help give some idea before start the project.

A. Software

The simulations of design are conducted using Finite Element Method Magnetic (FEMM) software. FEMM is a suite of programs for solving the low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains [3]..

i) DESIGN

Before run the simulation the design geometry is drawn on the software template. The electrode widths, number electrode and ground electrode are the variable parameter for geometry of design. The electrode width 0.2mm, 0.4mm, 0.6mm, and 0.8mm as varying parameter for the plate sensor. The length of electrode is set to 10mm. The plate sensor is divided into two major types which are with ground at backplane and another is without ground at backplane.

Besides plate structure, another design is square box structure. The three difference electrode width 2mm. 6mm and 10mm is designed. For this square box design, the electrode width, gaps between electrodes and the number of electrode is considered. The length of electrode is fixed to 10mm for both plate and square box structure.

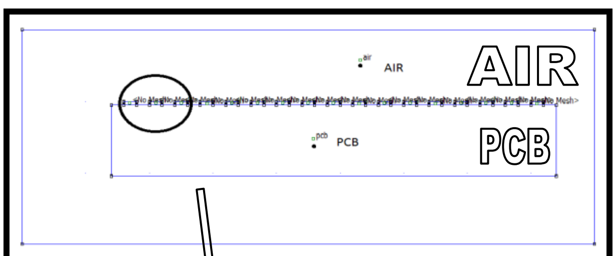

Figure 3. Design Draw

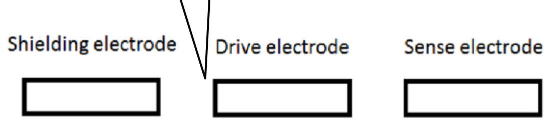

Figure 4. Design Detail

The geometry of the sensor is designed with drive electrode and sense electrode is placed side by side each other. The arrangement shield electrode and ground may vary in each of the design.

ii) SIMULATION

The mesh were generate when simulation is running. The mesh can be set up before run the simulation. The proper mesh generation can get better result [2]. The percentage of dielectric constant (moisture) is simulated from 1% ($\varepsilon r1$), 20 %($\varepsilon r16$), 40 %($\varepsilon r32$), 60 %($\varepsilon r48$), 80 %($\varepsilon r64$) and 100 %($\varepsilon r80$) of moisture.

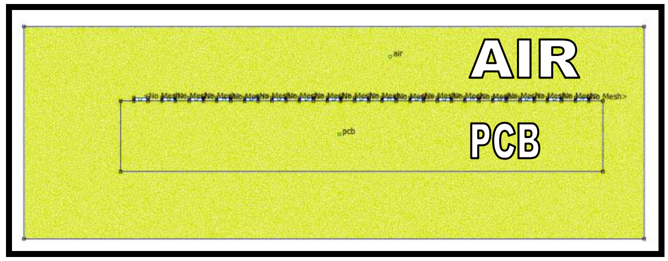

Figure 5. Mesh Generation

iii) RESULT

The quality of the results from software depends on model definition as long as mesh generation refinement [2]. The results with higher accuracy can be generated if the right model and mesh are chosen. The shape characteristic electric field is observed

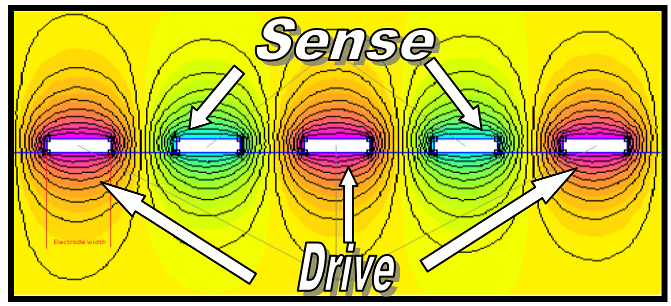

Figure 6. Simulation Result

The capacitance values were tabulate at each result. Then analyze the result to observe the best design.

B. Hardware

After several designs were simulated, selected geometry design was chosen to be fabricated using Printed Circuit Board PCB technology. Before fabrication process of design done, firstly the design must be drawn on the software. For this project, the Proteus software was used to draw the geometry design of soil moisture sensor. This software divide by two parts which is ISIS were use for circuit simulation and another part is ARES that use to design PCB layout..

i) DESIGN

The electrode width 0.6mm, 0.8mm, 1.0mm and 5.0mm are designed in software. There are two designs for plate structure and square box structure which is horizontal and vertical design. The number of electrode and electrode width is become variable parameter for plate structure. Then for the square box structure, big electrode width is chosen for observed penetration depth experiment. The designs that need to fabricate is require double layer PCB. During designing the layout, the bottom layer and top layer are determined in the software. The design double layer PCB due to backplane ground at the back of moisture sensor

As the design is double layer, the blue color is set to be bottom layer and the red color is top layer. The bottom layer is act as ground backplane. The size is set 50mm x 100mm for plate structure design and 80mm x 100mm for square box design. While the top layer of the PCB consist of number electrode. Figure 6 shows the PCB layout.

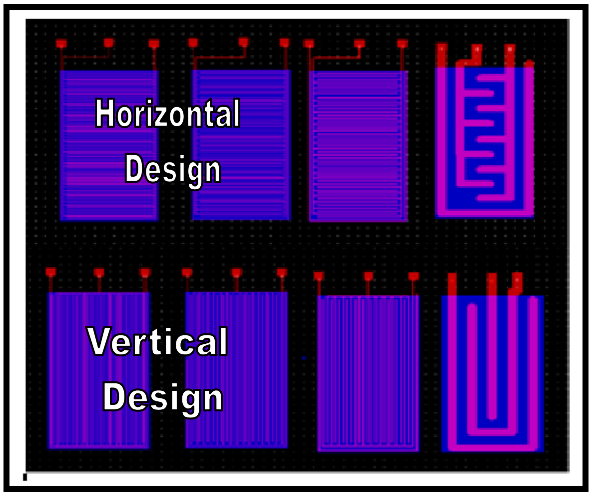

Figure 7. Design Plate Structure, Horizontal Electrodes (above) and Design Vertical Electrodes (below).

ii) PCB DEVELOP

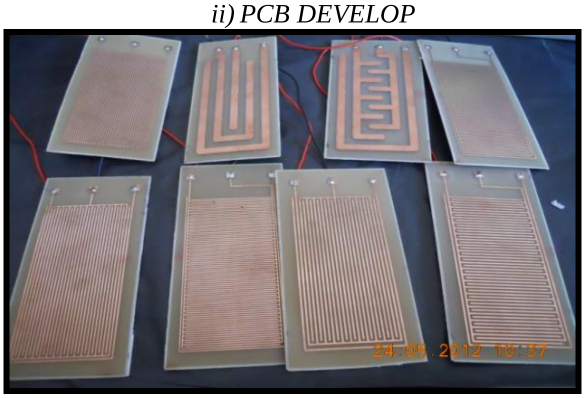

Figure 8. Completed PCB Plate Sensor

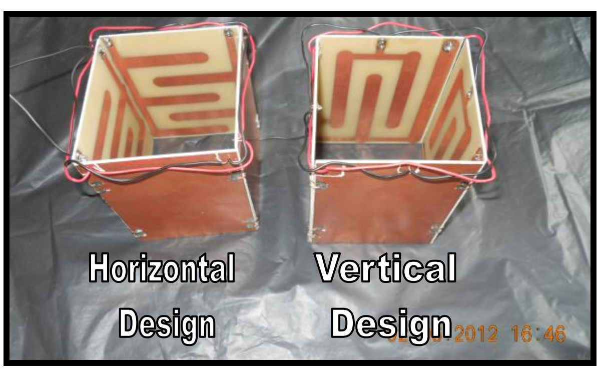

Figure 9. Completed PCB Box Square

The sensors are developing by using PCB technology. The double layer PCB is used to make this sensor. The PCB was developing at Fabrication Laboratory level 4 UITM. There are several steps for making PCB such as prints, UV expose, etching and many more.

iii) TESTING

After fabrication process of PCB is done. The sensors performance is analyzed by do several testing on it. The testing process is use LCR meter as tool to measure the capacitance value. The measured capacitance from the sensor is connected directly to LCR meter with 10 kHz of frequency. Usually the AC voltage source is applied to device under test (DUT). The meter measures the voltage across and the current through the DUT. From the ratio of these the meter can determine the magnitude of the impedance. After measure impedance internally and then converted for display to the corresponding capacitance.

Each of the designs is tested for several sample of soil. The samples of soil is using coconut pit and ranging from 1% to 80% Volumetric Water Content VWC. The sampling is using volumetric method. Volumetric method is where ratio water volume to soil volume. The 10% volumetric water content sample is actually 10% of water volume from soil volume.

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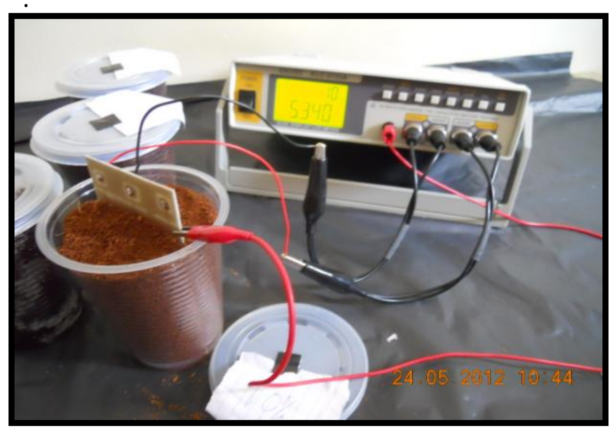

Figure 10. Test Set Up for FEF Soil Moisture Sensor

Each of Plate PCB is tested by 7 sample of soil which is 10% ,20%, 30%, 40%, 50%, 60%, and 80% of volumetric water content VWC. The characteristic of sensor board is observed by monitoring capacitance value

C. *Comparison*

The result between simulation and hardware testing is compared. The simulation result and the data obtain from hardware testing is plotted on the graph. All the data was tabulate in the table before it can be plotted on the graph. The graph was plotted to observe the characteristic of the moisture sensor due to geometry design.

IV. RESULT AND DISCUSSION

Based from the simulation result and testing data, the graph was plotted to determine the characteristic soil moisture sensor.

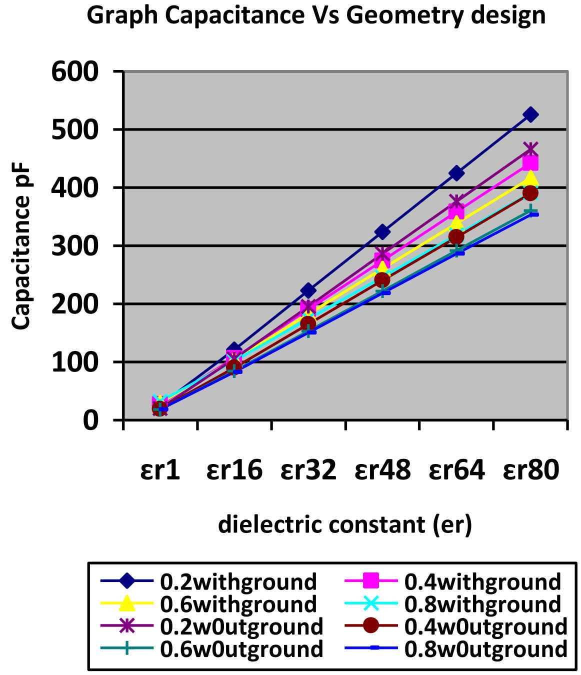

Figure 11. Graph Simulation Result

The graph on the figure 11 above shows the characteristic of moisture sensor in simulation. The capacitance value is increasing as the dielectric constant increases. Based from graph shows the moisture sensor design with ground and the electrode width 0.2mm (smaller) has the higher capacitance value than other at each dielectric constant percentage. While the lower capacitance value at each dielectric constant percentage is on design 0.8mm (larger) electrode width and without ground electrode

This graph also shows the capacitance value is increase when the electrode width value decrease. This shows that the electrode width do influence the capacitance's value of the sensor. The smaller electrode width gives bigger capacitance value. The smaller electrode width indirectly gives more number of electrodes if the size of sensor is fixed to be constant. It cause more plate of capacitor provided to generate the electric field. Thus, the sensitivity of sensor is increase. The ground electrode also influences the capacitance value. The sensor which has the ground electrode gives the bigger capacitance value. The ground electrode is controlled the flux distribution. When flux distribution well-organized the penetration depth can be increase. This is also one of the factors that determine the performance of the sensor.

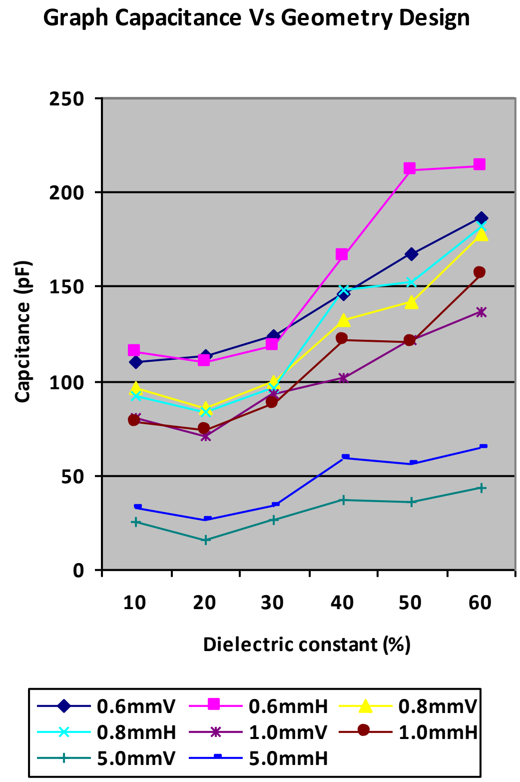

Figure 12. Graph Hardware Testing

The graph on the figure 12 above shows the characteristic of moisture sensor on actual hardware test. The capacitance value is increasing as the dielectric constant increases. Based from graph shows the moisture sensor with horizontal design and the electrode width 0.6mm (smaller) has the higher capacitance value than other at several dielectric constant percentages. While the lower capacitance value at each dielectric constant percentage is on design 5.0 mm (larger) electrode width and with vertical design.

This graph also shows the capacitance value is increase when the electrode width value decreases although graph is not linear. This shows that the electrode width do influence the capacitance's value of the sensor. The smaller electrode width gives bigger capacitance value. Thus, the sensitivity of sensor is increase.

The graph is not linear due to environment effect. During testing, the percentage of volumetric water content VWC in the sample changes accidentally causing the descending at the earlier of the graph. The human error can occur during sampling the soil. Based from the graph plotted shows that horizontal design is better than vertical design. The testing result is almost the same with the simulation result.

TABLE 1. TABLE CAPACITANCE VALUE DUE EFFECT GEOMETRY DESIGN (SIMULATION)

Electrode Width (mm)	Number of Electrode (drive)	Gaps Distance (mm)	Dielectric Constants (%)/ Capacitance (Pico Farad)		
			1	50	100
2	40	2	467.3	2078.7	3662.2
2	16	6	189.8	670.0	1015.9
6	16	6	447.0	1122.3	1723.8
6	20	2	528.6	1721.8	2906.0
10	8	10	330.2	765.7	1118.4

Table 1 shows that capacitance value due to effect of geometry design based from simulation result. This result simulation is from square box design. Based from data in the table, shows that increasing of dielectric constant value cause the capacitance increase. This phenomenon fulfills the theory of capacitance, which is capacitance is proportional to dielectric constant. This proved that the capacitance value is linear to the dielectric constant.

The next findings shows that numbers of electrode can increase the performance of FEF sensor. The more electrodes on the sensor can increase the capacitance value. The increased numbers of electrodes can indirectly decreasing the gaps between electrodes. This can be seen on the 6mm electrodes width simulation in the table 1 above.

Furthermore as can be seen from the table above, the value of capacitance is decreased as the gaps between electrodes are increases. The gaps is'd' in the formula equation of capacitance. The testing is support the formula equation which is the capacitance inversely proportional to the d, distance. This can be seen on the 2mm electrodes width simulation.

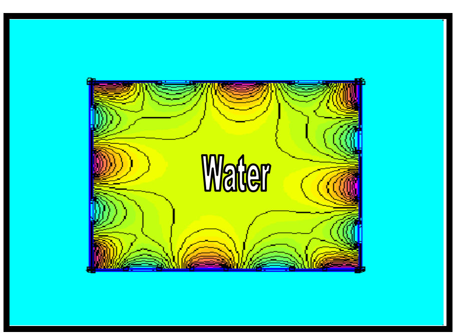

Figure 23. Square Box design Simulation with 10mm Electrodes width.

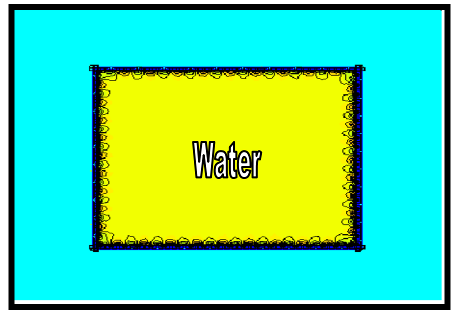

Figure 14. Square Box design Simulation with 2mm Electrodes width.

This next simulation is to observe the effect of using wider electrodes width on square box design. In this simulation, the electrode width is set 10mm that consists four drive electrodes, four sense electrodes and 10mm of length. From the figure 14, the penetration depth is improved by using wider electrode width. The electric field is penetrating more to the material. The difference with 2mm electrodes width, the Figure 13 shows that less penetration of electric field into the material.

TABLE 2. TABLE CAPACITANCE VALUE DUE EFFECT GEOMETRY DESIGN (TESTING)

Electrode Width (mm)	Types of Design	Dielectric Constant (%)/ Capacitance (Pico Farad)			
		1%	10%	40%	80%
10mm	Horizontal	68.5	128.9	174.6	3786.2
10mm	Vertical	69.8	131.5	187.3	4938.1

Table 2 shows that capacitance value due to effect of geometry design based from actual testing result. This data is from actual square box structure. The data in the table shows that not many difference between horizontal design and vertical design.

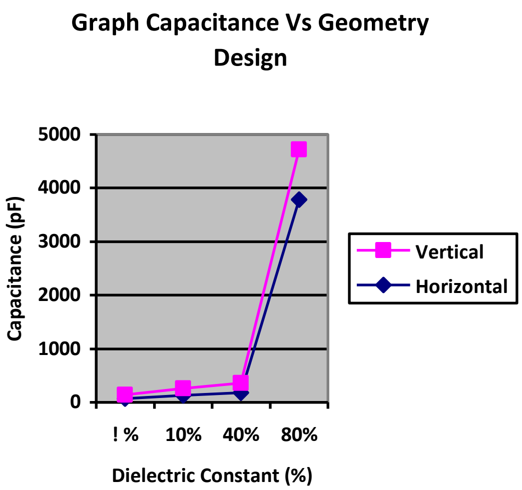

Figure 15. Graph Actual Hardware Testing

The graph on the figure 15 above shows the characteristic of moisture sensor on actual hardware test. The capacitance value is increasing as the dielectric constant increases. The data are similar for both designs. As result from experiment before, this experiment also shows that capacitance is linearly to dielectric constant.

V. CONCLUSION

The paper concluded that FEF sensor is linearly proportional to the dielectric constants. The small difference between simulation data and testing result obtained could be explained due to environment effect. Besides, the samples of soil were prepared using volumetric method that will not have 100% uniformity of moisture in any part of the sample. There will be some error mixture in sampling the soil but not more 5% error. The experiments showed the smallest electrode width and more number of electrode cause more sensitive to presence of a material or estimate the concentration of a material. The sensitivity also can be increase by increasing the number of electrodes. Besides that the small gaps between electrodes can help increase the sensitivity. The shield and ground electrode at the back plane make electric field more concentrate thus penetration depth could be increase. Penetration depth also can be increased by use wider electrode width. Geometry design also do influence to the performance. Although there is no analytical model for FEF sensor, but from this experimental work shows that the plate structure sensor with horizontal design has good performance than the sensor with vertical design. For the square box structure vertical design and horizontal design is slightly similar each other. Lastly the geometry of design can be chosen depend on their application.

FUTURE RECOMMRNDATION

During testing on the actual hardware sensor, the result is influence by environment effect. The testing should be done in covered oven to reduce environment effect. The volumetric method for sampling the soil with water should be mixture uniformly The numerical simulation and testing should be done Include the geometry of electrodes(shape) and substrate, the choice of materials for electrode and substrate, and the arrangement of guard electrodes to optimize the performance of the sensor.

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