SKRIPSI

ESTABLISHMENT OF CURRENT

AND CHARGING-DISCHARGING OF CAPACITOR

OLEH

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SKRIPSI INI DIAJUKAN UNTUK MELENGKAPI SEBAGIAN PERSYARATAN MENJADI SARJANA TEKNIK

DEPARTEMEN TEKNIK ELEKTRO
FAKULTAS TEKNIK UNIVERSITAS INDONESIA
NOVEMBER 2008

PERNYATAAN KEASLIAN SKRIPSI

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ESTABLISHMENT OF CURRENT

AND CHARGING-DISCHARGING OF CAPACITOR

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PENGESAHAN

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ESTABLISHMENT OF CURRENT

AND CHARGING-DISCHARGING OF CAPACITOR

Dibuat untuk melengkapi sebagian persyaratan menjadi Sarjana Teknik pada Program Studi Teknik Elektro Departemen Teknik Elektro Fakultas Teknik Universitas Indonesia. Skripsi ini telah diujikan pada sidang ujian skripsi pada tanggal 24 Oktober 2008 dan dinyatakan memenuhi syarat/sah pada Departemen Teknik Elektro Fakultas Teknik Universitas Indonesia

Depok, 7 November 2008

Dosen Pembimbing

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The students have gotten much information, knowledge and experience about the theory and practical of electromagnetic field area, concentrate in current and capacitance of parallel conductor which acts as capacitor as a part of becoming a professional engineer.

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ABSTRAK

Tugas akhir ini dijalankan atas dasar untuk membuktikan bahwa kapasitansi, yang diukur dalam satuan Farad, diantara konduktor-konduktor paralel memiliki besar kapasitansi yang sama tetapi berbeda tanda (+/-). Selanjutnya, proyek ini dilakukan untuk menunjukkan bahwa arus listrik mengalir di dalam konduktor oleh pergantian arus (displacement current) dan dipengaruhi oleh penurunan tegangan (voltage drop) di segala bentuk konfigurasi pengaturan konduktor-konduktor secara paralel.

Pelaksanaan tugas akhir ini menggunakan program Finite Element Method Magnetics (FEMM) simulasi 2D planar untuk problematika elektromagnetik. Seluruh simulasi telah dilakukan semaksimal mungkin untuk menunjukkan hasil yang baik untuk mendukung teori-teori yang telah ada. Program ini dianggap cukup mampu untuk mengukur medan elektromagnet dan besar kapasitansi

Keterbatasan yang dialami dalam pelaksanaan tugas ini adalah program ini tidak dapat menunjukkan hasil output gelombang arus untuk setiap konduktor-konduktor paralel yang diberi tegangan/ arus masuk.

Tujuan proyek ini adalah untuk memperdalam dan memperjelas pengetahuan penulis di dalam dasar-dasar keelektromagnetikan, khususnya di bidang hukum kapasitansi untuk di masa depannya.

ABSTRACT

The aim of this project is to show that capacitance between parallel conductors are having the same magnitude with different signs if applied with a step voltage and assumed in a free space. The second aim of the project is to prove that the current flows in conductors is by the displacement current and affected by voltage drop in four parallel conductor's configuration. The third aim of this project is to show the behavior of parallel plate cable and capacitors during the charging and discharging state.

This project uses Finite Element Method Magnetics (FEMM) 2D planar in electromagnetic problem as the supporting software to do the simulation. All simulations have been done to prove results to support theories in practical world. The software is able to show the electromagnetic field and capacitance magnitude.

For the laboratory experiments, this project uses a specially designed circuit to charge the capacitors with a step voltage. The measurements that occur meant to show the applied voltage and the terminal currents of the capacitors.

The limitation found in the software is that it can not show current waveform output if the parallel conductors injected with step voltage/current.

The limitation found in the circuit is that it cannot drive a fast voltage to charge the capacitors.

The importance of the project is to give students a deeper and clear knowledge in fundamental of electromagnetism especially in capacitance law consciousness for the future.

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1. Introduction

1.1 Project Value

The aim of this project is to show that capacitance between parallel conductors are having the same magnitude with different signs if applied with a step voltage and assumed in a free space. The second aim of the project is to prove that the current flows in conductors is by the displacement current and affected by voltage drop in four parallel conductor's configuration. The third aim of this project is to show the behavior of parallel plate cable and capacitors during the charging and discharging state.

1.2 Objective

This project uses Finite Element Method Magnetics (FEMM) 2D planar in electromagnetic problem as the supporting software to do the simulation. All simulations have been done to prove results to support theories in practical world. The software is able to show the electromagnetic field and capacitance magnitude.

For the laboratory experiments, this project uses a specially designed circuit to charge the capacitors with a step voltage. The measurements that occur meant to show the applied voltage and the terminal currents of the capacitors.

1.3 Limitation

The limitation found in the software is that it can not show current waveform output if the parallel conductors injected with step voltage/current.

The limitation found in the circuit is that it cannot drive a fast voltage to charge the capacitors.

1.4 Project Purpose

The importance of the project is to give students a deeper and clear knowledge in fundamental of electromagnetism especially in capacitance law consciousness for the future.

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2. Theory

2.1 Capacitance

Capacitance is the amount of charge something can hold for a given applied potential difference between separated parts of conductor $C = \frac{Q}{V}$. Two parallel conducting plates parallel to each other separated by an insulator. The conductors usually have charges of equal magnitude and opposite sign thus the net charge of the capacitor is zero. The electric field between two conductors is proportional to the magnitude of this charge and potential difference between conductors and the charge magnitude. The field between the plates is basically uniform, except for some fringing at the edges and the charges on the plates are uniformly distributed over the opposing surfaces.

2.1.1 Capacitance between Parallel Conductors

Two plates of area A, spacing d, with equal and opposite charge±Q

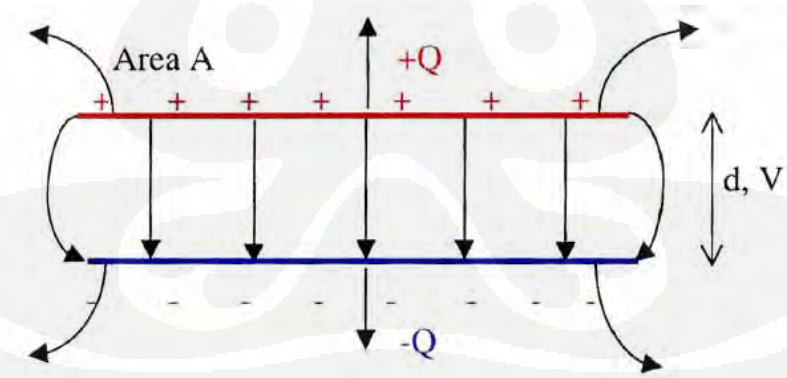


Figure 1 Conducting Parallel Conductors

The charge Q and the potential difference V are proportional:

$$\mathbf{Q = CV_{ab}} \quad \ldots.. (1)$$

Unit: 1 Coulomb/Volt = 1 Farad (F); after M. Faraday, 1830

$$\int_{surface} E \cdot dA = \frac{\sum q_{enclosed}}{\varepsilon_0} \qquad \text{..... (2)}$$

$$E = \frac{V_{ab}}{d} \qquad \text{..... (3)}$$

$$\sigma = \frac{Q}{A} \qquad \text{..... (4)}$$

Thus,

$$EA = \frac{1}{\varepsilon_0}\sigma A \qquad \text{..... (5)}$$

$$E = \frac{\sigma}{\varepsilon_0} \qquad \text{..... (6)}$$

According to $Q = CV$,

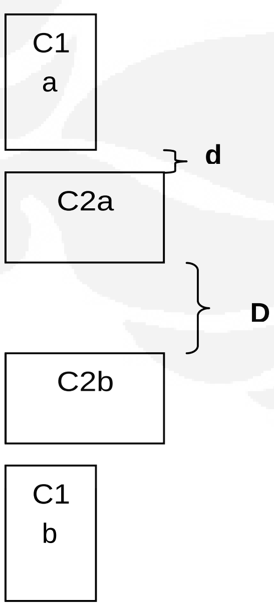
$$C = \frac{Q}{V} \qquad \text{..... (7)}$$

$$C = \frac{\sigma A}{\left(\sigma/\varepsilon_0\right)d} = \frac{\varepsilon_0 A}{d} \qquad \text{..... (8)}$$

By zero volt applied to the bottom plate, the formulas can be all re-written with negative sign (-).

This shows parallel plate capacitor capacitance depends on area and plate separation.

In the next situation conductors are arranged as:



These same sizes conductors are applied to a step voltage assumed as 10 V in a free space. When the voltage applied, conductors act as capacitor when the electric and magnetic field rises. Capacitance for the two top conductors are :

C1a : 4.98872pF/m

C2a : 11.3709pF/m

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C1b and C2b have the same magnitude with different sign with the top conductors. The magnitude of capacitance depends on how big is the electric field surround the conductors where it makes the C2a has almost three times bigger capacitance than C1a. Where it can be derived from the voltage, charge and capacitance formula, charge and voltage are proportional, thus voltage applied is the main factor for this difference. Formula: C = Q/V.

From Figure 2, it can be seen that the pink colored area shows 9.5V that makes the centre area between conductors have a big electric field magnitude. C2a positioned as horizontal, thus the capacitance is bigger and also for the reason it has the nearest distance with the zero voltage applied conductors below.

Figure 2 Surrounding Voltage Image

2.2 Displacement Current

Good conductors store a lot of electrons in the conduction band, which are influenced by electric field. When the electric field is applied, the electrons will move. The movements of the electrons will produce conduction current.

Conductivity and current has linear relationship. High conductivity results in high current, and according to magnetic field equation:

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$$H = \frac{I}{2\pi r} \qquad ..... (9)$$

high magnetic fields are also produced, resulting in opposing change and limiting the current velocity.

Every movement of current produces internal electric fields induced inside the conductor, resulting in internal conduction electrons and eddy currents. Eddy currents oppose any change in internal conduction currents and producing power loss due to the finite conductivity, resulting in attenuation of the electromagnetic waves movement in the conductors. To overcome these difficulties, the electromagnetic waves need to change the current flow with associated displacement current which may establish conduction currents on the surface of the conductors and diffusing into the interior.

The formula of displacement current density is:

$$J_D = \frac{\partial D}{dt} \qquad ..... (10)$$

where D is the electric flux density. The displacement current is expressed as:

$$I_{Disp} = \int J_D . dS = \int \frac{\partial D}{dt} . dS = \int \varepsilon_o \varepsilon_r \frac{dE}{dt} . dS \qquad ..... (11)$$

Thus, displacement current is a result of time-varying electric field and influenced by permittivity. Displacement current can also be considered as a result of magnetic field, as per equation:

$$\nabla \times H = I_{Disp} \qquad ..... (12)$$

Even in a vacuum, displacement current still exists because the magnetic field is producing internal conduction current, resulting in internal electric field.

2.2.1 Capacitor Displacement Current

Displacement current in a capacitor is produced by the capacitive effect and is often equated with circuit capacitive current, according to the equation

$$I_{Disp} = I_C = C \frac{dV}{dt} \qquad ..... (13)$$

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However, capacitive current is produced by displacement current propagating at high velocity within the insulation medium of the capacitor.

Consider a rectangular capacitor to be transverse electromagnetic (TEM) transmission line with open circuit at one end.

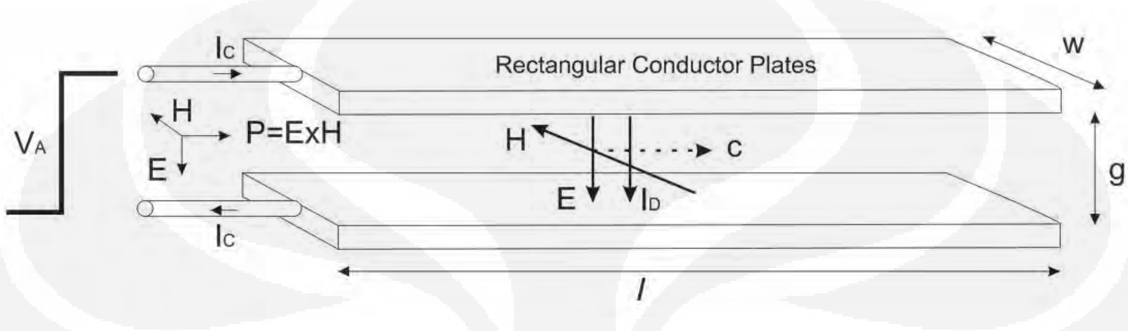

Figure 3 Initial Propagating Wavefront

When a step voltage V_A with current I_C is applied across the input of the capacitor, electric field E propagates along the plates and magnetic field H exists in the medium separating the capacitor plates. Any changes in the electric field resulting in a displacement current, as per equation

$$I_D = \frac{\Delta E}{Z_o} \qquad \text{..... (14)}$$

where Z_o is the characteristic impedance of the space between the plates. The characteristic impedance is also known as the field impedance Z_f.

The E and H fields direct power into the space between the plates via Poynting vector $P = E \times H$.

The system is an open circuit transmission line with the following characteristic:

Intrinsic Impedance of Medium, $Z_m = \sqrt{\frac{\mu}{\varepsilon}} = 377\Omega$ for free space ..... (15)

Number of Parallel Cells, $n_c = \frac{L_H}{L_E} \approx \frac{w}{g}$, neglecting fringing ..... (16)

Field Impedance, $Z_f = Z_o = Z_m \frac{L_E}{L_H} = \frac{g}{w} Z_m$ ..... (17)

Line Capacitance, $C = \varepsilon_o \varepsilon_r n_c \; F/m$ ..... (18)

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Total Capacitance, $C_T \approx \varepsilon_o \varepsilon_r \frac{wl}{g} F$ ..... (19)

Line Inductance, $L = \frac{\mu_o \mu_r}{n_c} \approx \mu_o \mu_r \frac{g}{w} H/m$ ..... (20)

2.3 Establishment of Currents

Current flow in conductors is by displacements currents in the insulating material, which set up the surface currents, followed by diffusion of these surface currents into the interior of the conductor. Regularly, conductors are place in parallel to increase the current carrying capability of a system. Furthermore the arrangement of conductors will affect the ability of conductors to share currents when the currents are continually altering.

For situation below, there are 2 conductors have square cross section of width **w**, labeled C1 and C2, applied with Voltage Vo. Consider the conductors in a lossless medium such a free space. Capacitance C2 has figured is twice bigger than capacitance in C1. Between C1 and C2 there is a **d** gap and **D** gap applied to separate top conductor set to the bottom conductor sets. C1 and C2 from the top set and the bottom set have reciprocal charge value (Q) with equal and opposite charge.

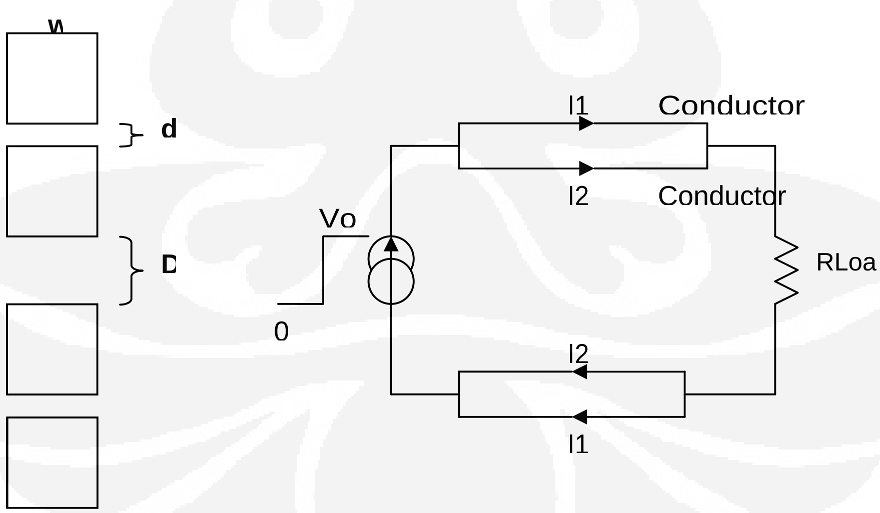

Figure 4 Circuit Schematic

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By closing the switch, line current is established on the surface of the conductors by the propagation of electromagnetic energy in the free space between the conductors.

As soon as voltage/ current applied to the conductors it sets up the cross electric field

E = $\frac{Vo}{d}$ and its associated magnetic field (H). With resultant displacement current I_D = Vo/Zo. Zo is the characteristic field impedance of the conductors Zo = $\sqrt{L/C}$ and the velocity of propagation is velocity, v = $1/\sqrt{LC}$. Assumed velocity is light velocity $3x10^8$m/s in the vacuum of free space. The current flows along the surface of the conductors and slowly diffuses into the interior of the conductor with appearance slight voltage drop along its length.

The experimental result shows that at the beginning current applied, I1 and I2 rise:

$$I1 = \frac{2}{3} xIo$$

$$I2 = \frac{1}{3} xIo$$

Where it turns out to be $1/2$ Io A at the end, as shown in I graphics below with respect to time (t).

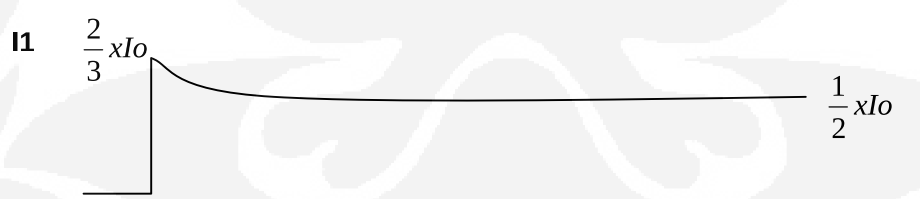

Figure 5 C1 Current Output

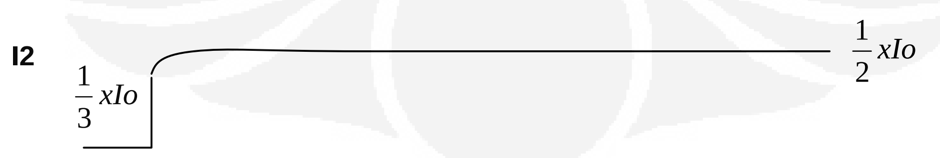

Figure 6 C2 Current Output

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The Displacement Current Density is $J_D = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t}$ A/m^2

This displacement current density is proportional to the capacitance/unit length, in this case is capacitance/m. This explains the magnitude of current at the beginning voltage applied to the conductors. The current is proportional to the capacitance magnitude, where:

$$I_D = \int_{surface} J_D \cdot ds = Io = \frac{Vo}{Zo} \text{ A} \qquad \text{..... (21)}$$

For I1, as the voltage decays, the current gradually decrease to 0.5Io. The voltage has drop half of the input signal in the resistor, thus the current become half of input current. The voltage drop across the C1 generates electromagnetic fields and induces C2.

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2.4 Charging Capacitors by a Voltage

This is the basic theory of charging a capacitor in a perfect situation where no loss is introduced.

2.4.1 First Inwardly Going Wavefront (Charging to V_A)

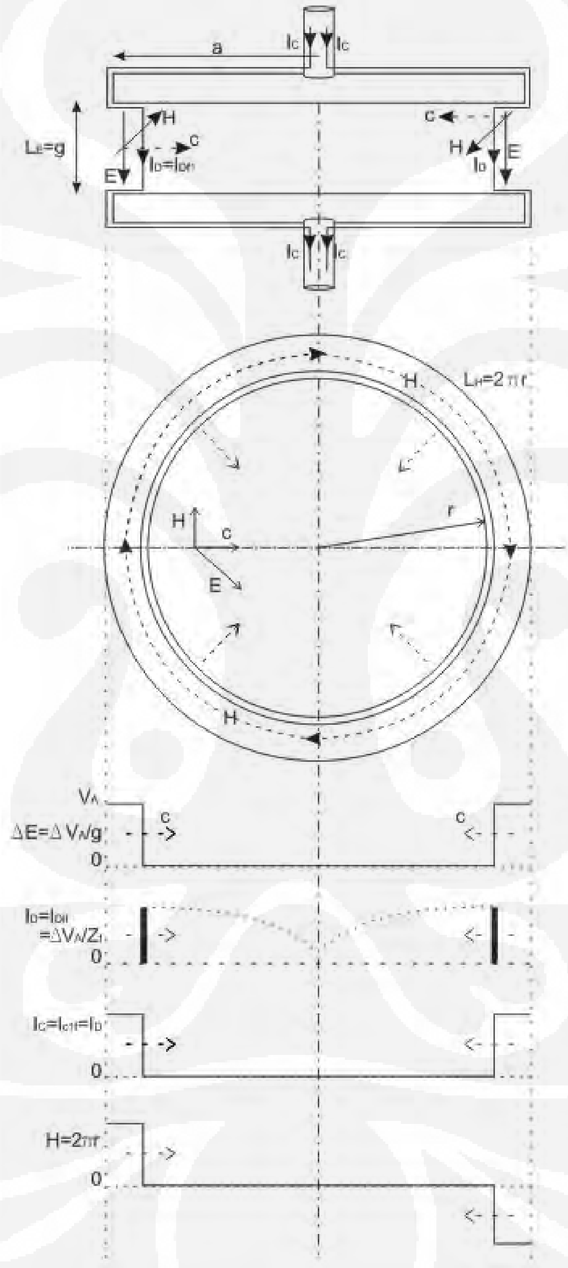

Figure 7 First Inwardly Going Wavefront

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When the step voltage V_A is applied to the capacitor, the electric field ($E = \frac{V_A}{g}$) starts at the outer edges of the capacitor and produces the displacement current ($I_D = \frac{V_A}{Z_f}$) in the outer edge spaces between the plates. The displacement current will produce magnetic field ($H = \frac{I_D}{2\pi r}$).

As ΔE and I_C moving towards the centre, the energy Poynting vector ($S = E \times H = P$) is also moving towards the centre. Thus, the electrostatic energy and magnetic energy are added to the space of the capacitor.

The displacement current, electric and magnetic fields start at the outer edges of the capacitor and propagate in towards the centre. As the E&H fields propagate inwardly, the field impedance Z_f increases due to the reduction of the length of the H field resulting in decreasing of the displacement current. At the centre of the capacitor, the displacement current is reduced to zero and the wave is reflected back to the edges.

The conduction current ($I_C = I_{C1f} = I_{D1f}$) also flows on the outer surfaces of the capacitor and suffers a voltage drop due to its high resistance.

When the wave reaches the centre of the capacitor, the space between the plates has been charged to a potential of V_A volts and contains of equal amounts of electrostatic and magnetic energies.

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2.4.2 First Outwardly Returning Wave (Charging to $2V_A$)

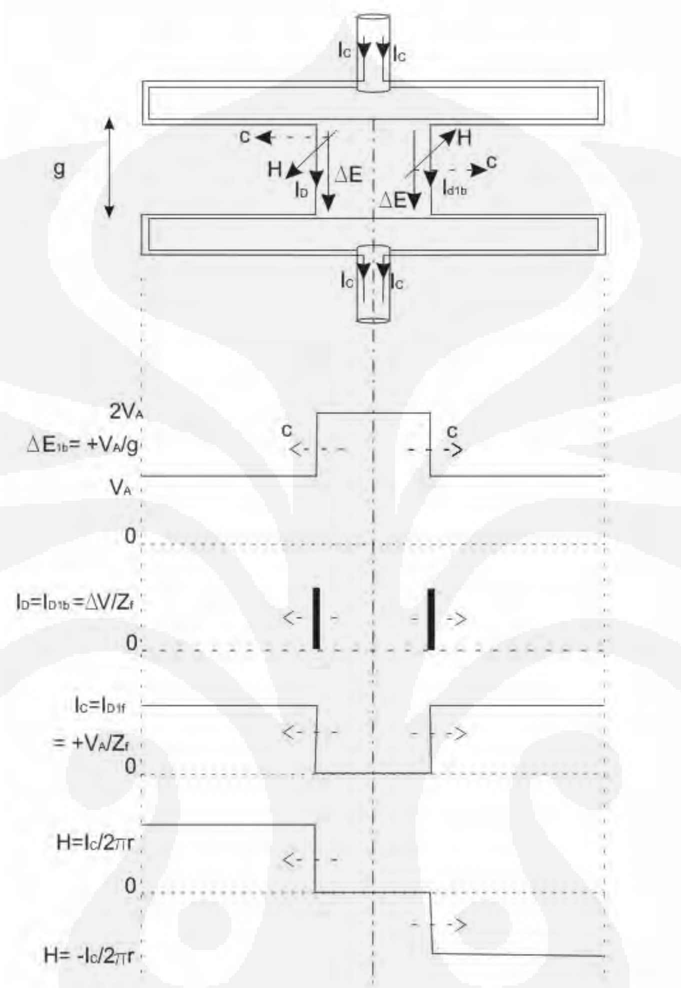

Figure 8 First Outwardly Returning Wave

As the wave reached the centre of the capacitor, it is moving back towards the edge. During this transition, the reflected wave interacts with the inwardly going wavefront. This situation causes the E field is unchanged, resulting in doubling the line voltage to $2V_A$, and the line current reserved, resulting in zero line current and reversed H field.

During this transition, the continuous incident power ($P = E \times H$) and the stored magnetic energy is converted into electrostatic energy. Since the E field doubles to $2V_A/g$, the electrostatic energy of the capacitor is multiplied by 4.

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As ΔV remains unchanged, the displacement current $I_D = I_{D1b} = \frac{V_A}{Z_f}$ also remains unchanged.

When the wave is returning to the edges, the space that was filled by the returning wave is charged to a voltage of $2V_A$ volts and having a conduction current I_{C1B} of zero.

2.4.3 Second Inwardly Going Wave (Discharging to V_A)

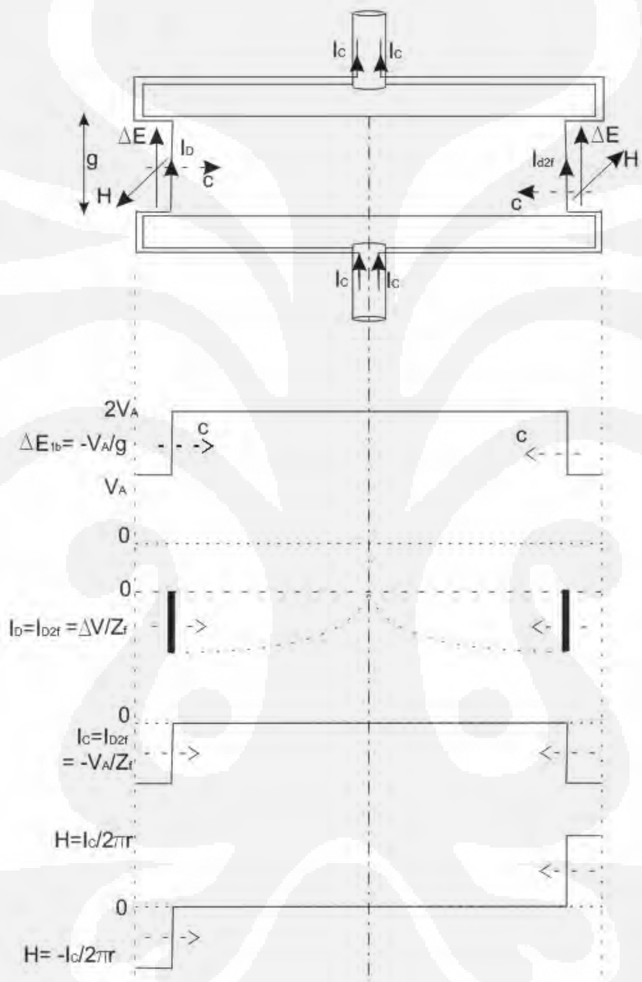

Figure 9 Second Inwardly Going Wave

When the reflected wavefront reaches the outer edge of the capacitor, the voltage is set back to the voltage level of V_A, and the second inwardly going wave propagates into the centre of the capacitor. At this stage, $\Delta V = -V_A$ and $I_D = -\frac{V_A}{Z_f}$, and the capacitor voltage is halved. Thus, the electrostatic energy is divided by 4. A quarter of the energy is converted to magnetic energy, and the half is returned back to the supply. As the E field drops, $\Delta E = -\frac{V_A}{g}$

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and the displacement current I_{D2f} reversed in accordance to negative ΔV. Since the capacitor is discharging, the conduction current $I_{C2f} = I_{D2f}$ flows out of the capacitor to the source.

As the wave is travelling, the space between the capacitor is charged to the voltage of V_A and the magnetic field is reversed from the transition between the first inwardly going wavefront, since both the displacement and conduction currents are reversed.

2.4.4 Second Outwardly Returning Wave (Discharging to 0V)

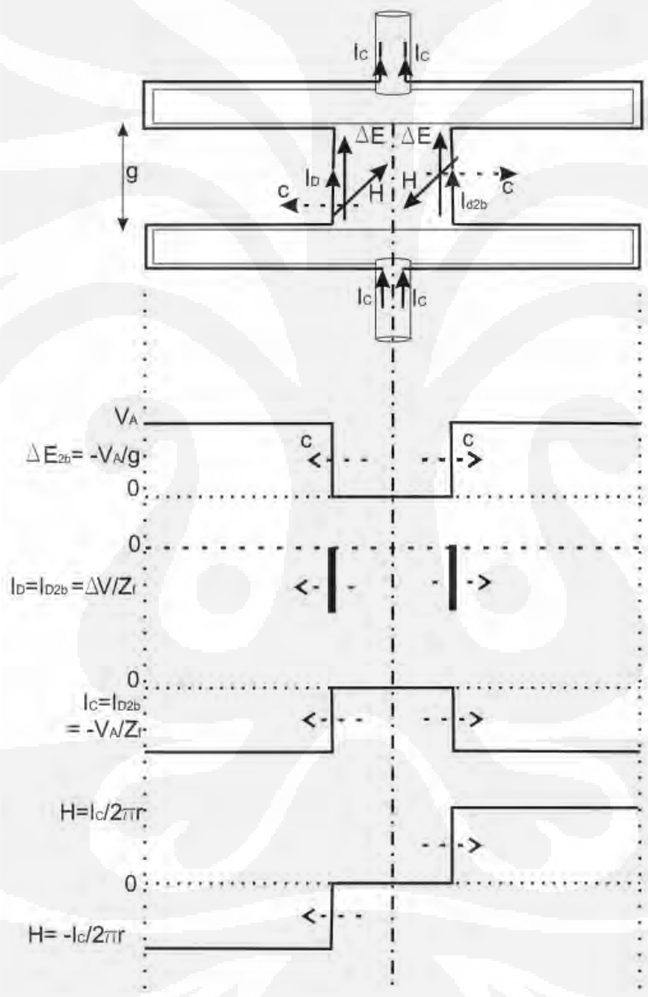

Figure 10 Second Outwardly Returning Wave

During this transition, ΔE of the returning wave is negative, as was the incident wave, so that the interaction between the waves resulting in zero conduction current and ΔE. As ΔE is negative, the displacement current in this transition is also negative, causing the conduction current to flow back to the supply.

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Since the E&H field are both reduced to zero, the electrostatic and magnetic energies are turned to the supply.

2.4.5 Steady-State Situation after N Transitions

The steady-state situation is indicated by the voltage and current waveforms shown in Figure 11 below as functions of time.

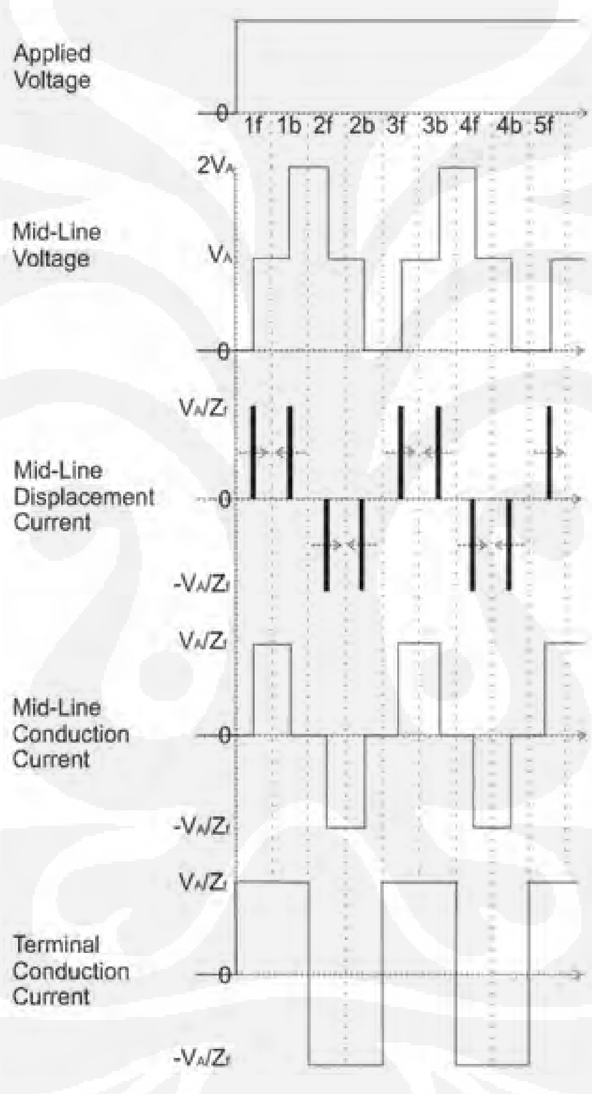

Figure 11 Steady-State Situation after N Transitions

When a terminal voltage of the capacitor rises by V_A, the internal voltage of the capacitor oscillates between $2V_A$ and zero. The figure shows that the midline being the circle half into the capacitor at a radius of a/2. Displacement currents are produced when there is a change in

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E field. The directions of the displacement currents affect the directions of the conduction currents. Thus, the displacement currents affect the mid-line and terminal conduction current.

2.5 Charging Capacitors by a Voltage with Losses

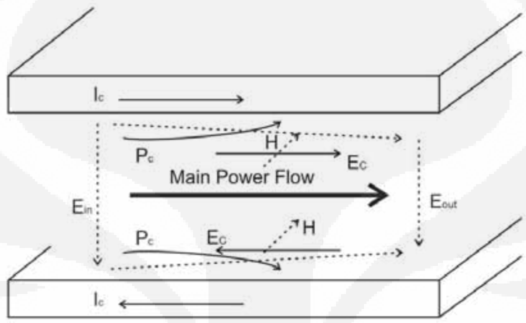

Figure 12 Diagram of Losses during Electromagnetic Propagation

As stated before, electromagnetic waves propagating along the capacitor produce conduction currents. The currents through the surface of the capacitor that has high resistance, resulting in high ohmic voltage drop which moves along the capacitor. Thus the electric fields of the voltage drop (E_C) drives power P_C consists of the losses, which flows into the capacitor plates through the inner conductor surfaces.

The transverse E field that drives the main power continually falls as the wave moves into the capacitor. This decrease occurs when on every forward transition producing decreases on the ΔE field amplitude so that the rise time is getting longer. This may result in the decreasing and widening of the displacement and conduction currents. The waveforms of the mid-line voltage, mid-line displacement current, mid-line conduction current, and terminal conduction current are illustrated in Figure 13 below.

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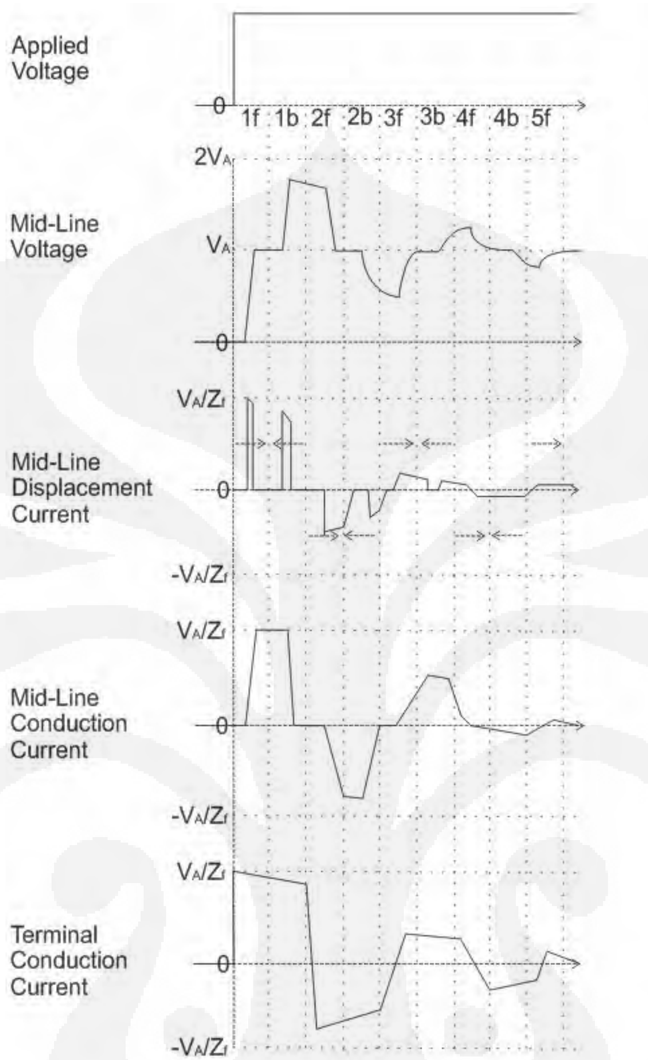

Figure 13 Steady-State Situation after N Transitions with Losses

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3. Practical Laboratory Experiments on Charging and Discharging of Capacitors

The purpose of the experiments that have been done is to prove the theory about the charging of a capacitor. For these experiments, the students developed a device to apply step voltage to the capacitors so that the electromagnetic waves propagate along the surface of the capacitor. Thus, the voltage and the terminal current of the capacitor can be observed.

The circuit diagrams of the device are shown in Figure 14 and Figure 15.

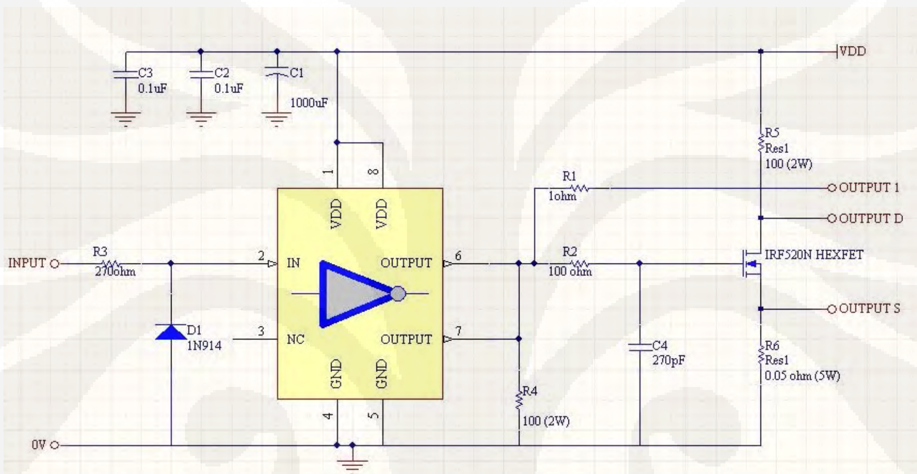

Figure 14 Schematic Diagram of the Charging Circuit

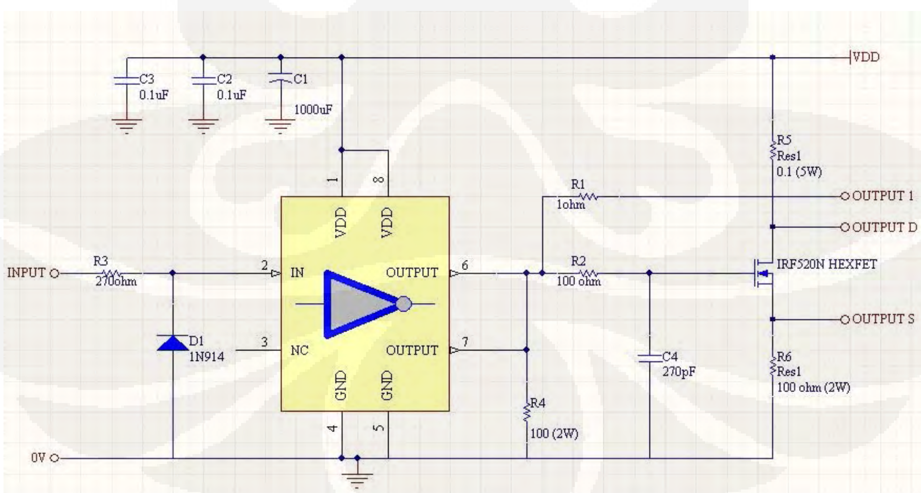

Figure 15 Schematic Diagram of the Discharging Circuit

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The function of this device is to drive step voltages to the capacitor. For this device, a 6A high-speed MOSFET driver TC4420CPA chip manufactured by Microchip is used. The input of the device comes from a function generator with V_{DD} of 3V. The DC power supply is used to provide a DC voltage of 15V to turn the chip on.

The input from the function generator is connected to a 270Ω resistor that is used to reduce the currents going into the chip. Apart from that, a diode is connected to block the negative current from the function generator to flow to the input of the chip. If the current flows to the chip, it is most likely to break the chip. After proceeding through the resister and diode, the input flows into the chip.

Two 0.1µF ceramic capacitors are connected from pin 1 to 4 and pin 5 to 8. The purpose of these capacitors is to bypass the high frequency of the input to the ground. Another 1000µF capacitor is also connected from the input DC voltage to the ground. The purpose of this capacitor is to block the low frequency signals so that the voltage that energizing the device is smooth.

The output of the chip is divided to charge the capacitor and to feed the IRF520N HEXFET. A voltage divider power resistor of 100Ω 2W is connected to the ground to drive more current, while the chip output is connected to a 1Ω resistor before actually charging the capacitor. The other output from the chip is connected to the gain of the HEXFET after flowing through a 100Ω resistor and being filtered with a 270 pF capacitor connected to the ground.

To charge the capacitor, the drain of the HEXFET is connected to the DC voltage input through a 100Ω 2W power resistor. The source is shorted by connecting two 0.1Ω 5 W power resistors connected in parallel, with equal resistivity of 0.05Ω to the ground. The output of the HEXFET that is used for charging the capacitor comes from the drain.

To discharge the capacitor, the drain of the HEXFET is connected to the DC voltage input through a 0.1Ω 5W power resistor, so that the drain is shorted. The source is connected to the ground with a 100Ω 2W power resistor. The output of the HEXFET that is used for discharging the capacitor comes from the source.

The circuit is implemented into a PCB board to run the experiments. The design layout of the PCB is shown in the figure below.

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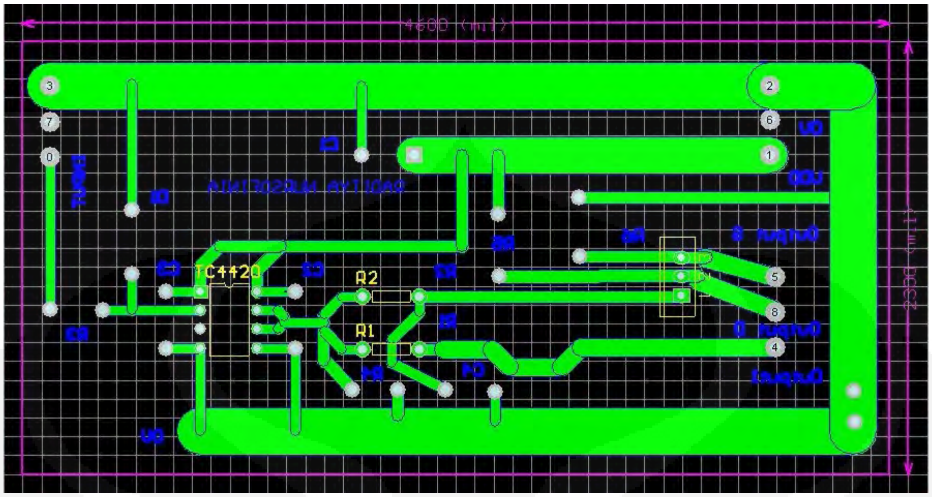

Figure 16 PCB Layout of the Circuit

3.1 Methodology of the Experiments

The experiments are done by testing parallel plate cables, a 6μF motor start capacitor, 0.56μF polyfoil capacitor, and a 4.7μF polycarbonate film capacitor.

Firstly, the device is connected to the inputs; the input of the chip is connected to the function generator while the V_{DD} is connected to the DC voltage. After that, the output from the chip and the HEXFET is connected to the experiment objects and connected to the oscillator to find the voltage V_A across the capacitor. For observing the behaviour of the capacitor during charging state, the other end of the capacitor is connected to the ground, while the observation of the terminal conduction current I_C is done by connecting the resistor of the source of the HEXFET with the oscillator.

To discharge the capacitor, while the output of the chip and the HEXFET is connected to one end of the capacitor, the other end is connected to a 0.1Ω 5W power resistor at the ground. The power resistor is connected to the oscillator to observe the terminal conduction current I_C.

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3.2 Experimental Results

3.2.1 Experiment 1: Charging and Discharging of Parallel Plate Cables

The cable that is used in these experiments is 14 m long and 10 mm wide with 0.1 mm gap between the plates. During the charging period, the results from the oscilloscope for voltage input from the chip and the HEXFET can be seen in Figure 17 and 18 below.

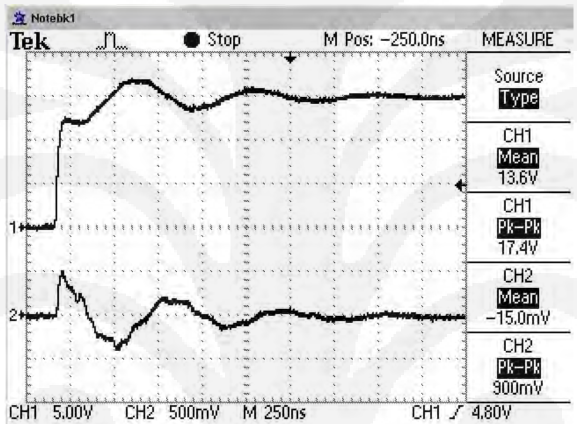

Figure 17 Experiment 1 Result: Charging Cable Using Chip Output

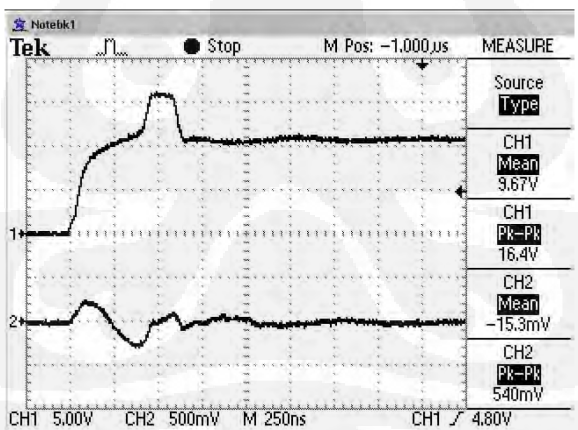

Figure 18 Experiment 1 Result: Charging Cable Using HEXFET Output

Channel 1 from the oscilloscope indicates the applied voltage to the charge the capacitor V_A. It can be seen that whilst the output from the HEXFET is more stable, the rate itself is quite low. Thus, for this experiment, the data that will be used is the voltage from the chip.

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Channel 2 from the oscilloscope indicates the terminal current of the capacitor during charging. It is obvious to see that the terminal current follows the terminal current from the theory, except for the ripples that is a result from the ohmic loss of the 0.5Ω resistor.

From the figure, it can be observed that during the first inwardly going wavefront, the capacitor is charged by an applied voltage of 12 V and having a terminal current of 4 A. Thus, the field impedance between the plates is 3Ω.

The result is quite accurate to the theory. According to equation 17,

$$Z_f = Z_o = \frac{g}{w} Z_m$$

With a gap of 0.1 mm, a width of 10 mm and Z_m of 377, the field impedance between the plates is 3.77Ω.

For the result during the discharging state can be seen in Figure 19 and 20 below.

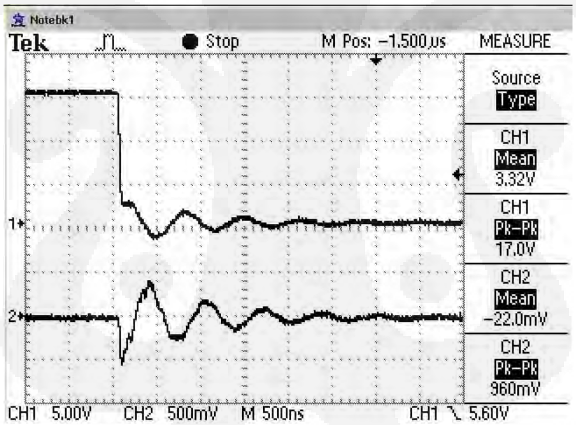

Figure 19 Experiment 1 Result: Discharging Cable Using Chip Output

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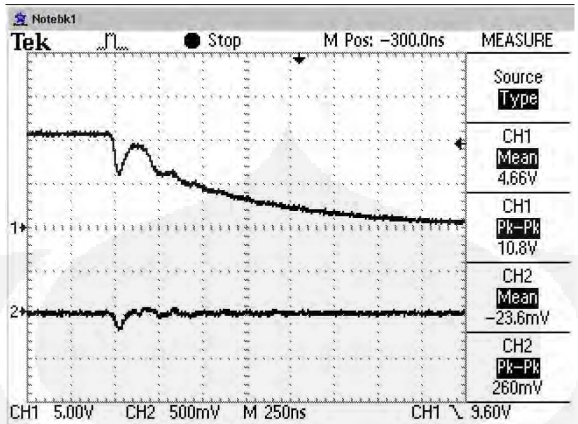

Figure 20 Experiment 1 Result: Discharging Cable Using HEXFET Output

And then again, it is obvious to see that the output from the HEXFET is not good enough to do this experiment, as the voltage drop occurs at a very slow rate. Even though the result from the chip is not good either, the figure shows that the voltage drop is not maximal, but it will be used as it is easier to observe.

From the figure, it can be observed that cable losses a voltage of 12V and having a terminal current of 5A. Thus, the field impedance between the plates is 2.4Ω.

3.2.2 Experiment 2: Charging and Discharging of Motor Start Capacitor

For these experiments, a 6µF motor start capacitor is charged and discharged by the output from the chip and the HEXFET.

During the charging period, the results from the oscilloscope can be seen in Figure 20 and 21 below.

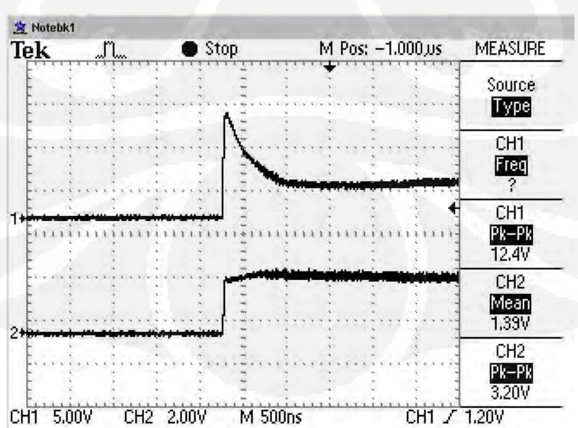

Figure 21 Experiment 2 Result: Charging Capacitor Using Chip Output

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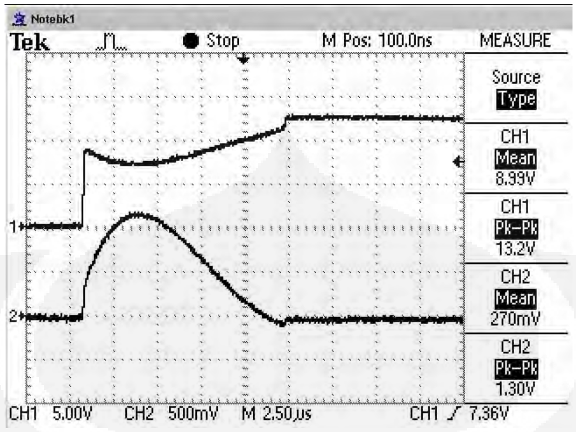

Figure 22 Experiment 2 Result: Charging Capacitor Using HEXFET Output

Channel 1 from the oscilloscope indicates the applied voltage to the charge the capacitor V_A. As the result from the chip is unstable, it is easier to do observation using the result from the HEXFET.

Channel 2 from the oscilloscope indicates the terminal current of the capacitor during charging. There is no negative current during the current establishment. This situation occurs because of the internal impedance of the capacitor.

From the figure, the first inwardly going wavefront occurs when a voltage of 8V applied to the capacitor. The terminal current itself rated at 4A. Thus, the field impedance of the capacitor is 2Ω.

During the discharging state, the results from the oscilloscope are shown in Figure 23 and 24 below.

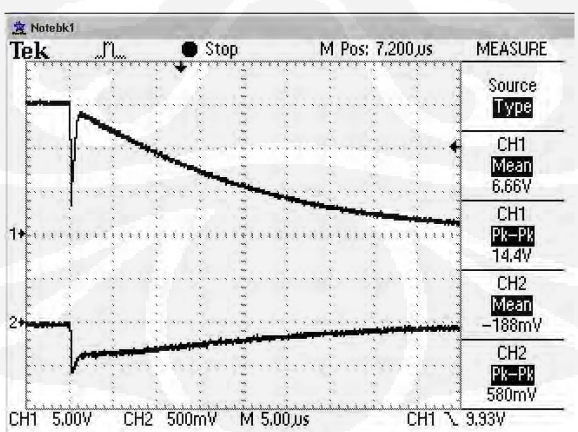

Figure 23 Experiment 2 Result: Discharging Capacitor Using Chip Output

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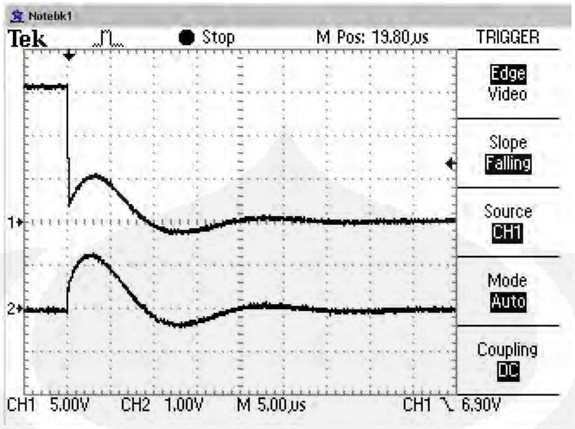

Figure 24 Experiment 2 Result: Discharging Capacitor Using HEXFET Output

From the figure above, it can be seen that the voltage drop of the capacitor is better when being discharged using the HEXFET output. Thus, this data will be used for the calculation. With a voltage drop of 12V and current of 20A, the field impedance of the capacitor during discharging state is 0.6Ω.

3.2.3 Experiment 3: Charging and Discharging of a Polycarbonate Film Capacitor

The capacitor that is used for this experiment is a 4.7µF polycarbonate film capacitor.

The result of the charging state of the capacitor from the oscilloscope can be seen in Figure 25 and 26 below.

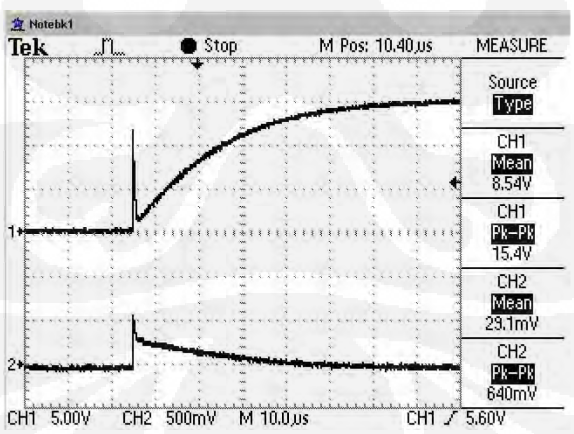

Figure 25 Experiment 3 Result: Charging Capacitor Using Chip Output

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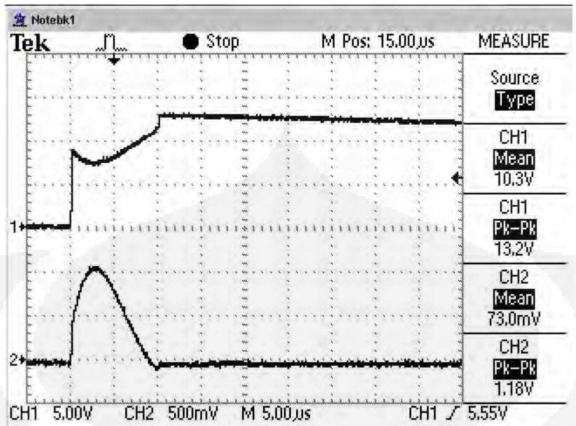

Figure 26 Experiment 3 Result: Charging Capacitor Using HEXFET Output

Channel 1 from the oscilloscope indicates the applied voltage to the charge the capacitor V_A. As the result from the chip is unstable, it is easier to do observation using the result from the HEXFET.

Channel 2 from the oscilloscope indicates the terminal current of the capacitor during charging. There is no negative current during the current establishment. This situation occurs because of the internal impedance of the capacitor.

From the figure, the first inwardly going wavefront occurs when a voltage of 8V applied to the capacitor. The terminal current itself rated at 4A. Thus, the field impedance of the capacitor is 2Ω.

During the discharging state, the results from the oscilloscope can be seen from Figure 27 and 28 below.

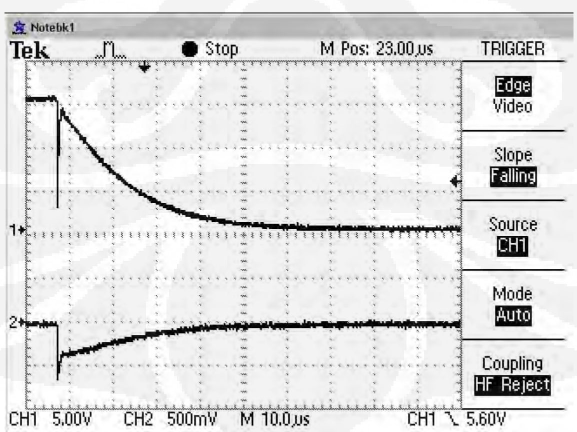

Figure 27 Experiment 3 Result: Discharging Capacitor Using Chip Output

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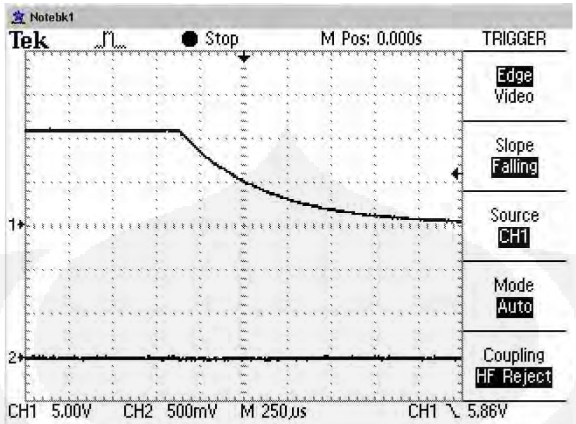

Figure 28 Experiment 3 Result: Discharging Capacitor Using HEXFET Output

From the figure above, it can be seen none of the results are satisfying. However, the result from the chip is easier to be observed. Thus, this data will be used for the calculation. With a voltage drop of 2V and current of 4A, the field impedance of the capacitor during discharging state is 0.5Ω.

3.2.4 Experiment 4: Charging and Discharging of a Polyfoil Capacitor

A 0.56μF polyfoil capacitor is used for these experiments.

During the charging period of the capacitor, the results of the experiments that are obtained from the oscilloscope can be seen on Figure 29 and 30 below.

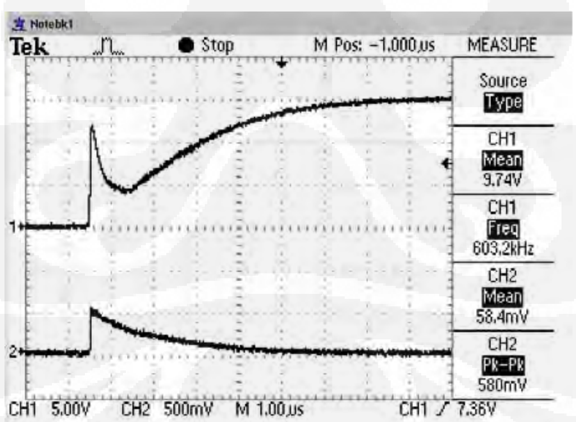

Figure 29 Experiment 4 Result: Charging Capacitor Using Chip Output

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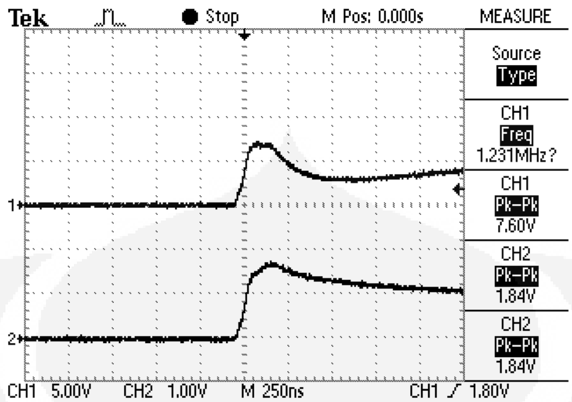

Figure 30 Experiment 4 Result: Charging Capacitor Using HEXFET Output

Channel 1 from the oscilloscope indicates the applied voltage to the charge the capacitor V_A. As the result from the chip is unstable, it is easier to do observation using the result from the HEXFET.

Channel 2 from the oscilloscope indicates the terminal current of the capacitor during charging. There is no negative current during the current establishment. This situation occurs because of the internal impedance of the capacitor.

From the figure, the first inwardly going wavefront occurs when a voltage of 8V applied to the capacitor. The terminal current itself rated at 8A. Thus, the field impedance of the capacitor is 1Ω.

During the discharging state, the results from the oscilloscope can be seen from Figure 31 and 32 below.

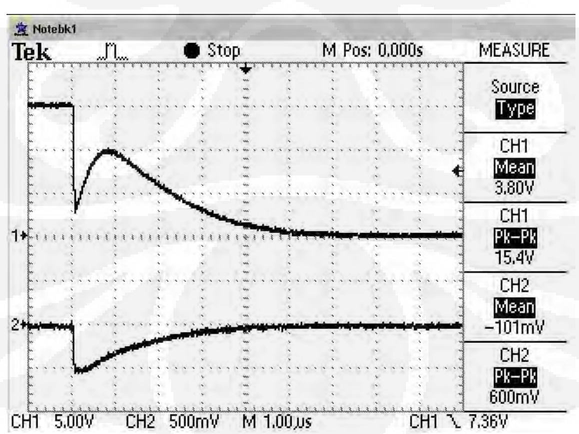

Figure 31 Experiment 4 Result: Discharging Capacitor Using Chip Output

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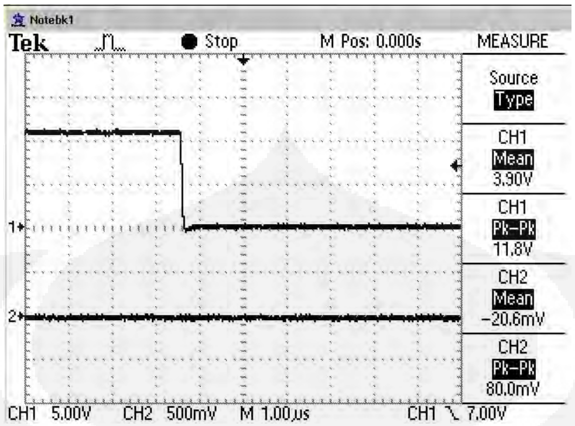

Figure 32 Experiment 4 Result: Discharging Capacitor Using HEXFET Output

From the figure above, it can be seen that the voltage drop of the capacitor is better when being discharged using the chip output. Thus, this data will be used for the calculation. With a voltage drop of 12V and current of 5A, the field impedance of the capacitor during discharging state is 2.4Ω.

It is regrettable that the output waveforms could not be obtained on the faster scale, due to the limitation of the circuit. If the circuit was able to drive the voltage faster, it is most likely to gain better result and resulting in deeper understanding about the behaviour of the capacitors during charging and discharging period.

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4. Software Simulation

4.1 ANSYS

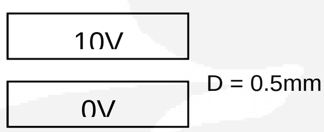
Due to issues with the software license, limitations of resources, different application from what it needed, author could not manage to take advantage of this software to do simulation

4.2 Finite Element Method Magnetic (FEMM)

FEMM is an open-source finite element package written by David Meeker. Finite Element Method Magnetics (FEMM) is a finite element package for solving 2D planar and axisymmetric problems in electrostatics and in low frequency magnetics. Packages of simulations have been done however; software could not simulate current diffusion. All simulations defined with input step voltages 0V to10V and have a boundary 5V for the surrounding area to prevent distortion. Surrounding area is assumed as air.

4.2.1 Simulation Set 1

a.



The simulation consists of 2 plates, upper plate and bottom plate which the plate sizes are 10mmx2mm. The size is adapted from the real conductor plates used in the hardware simulation by the other author, which has length approximately 14m. Results:

	Voltage (V)	Q (Coulombs)
Upper Plate	10V	2.91409e-08 C
Bottom Plate	0V	-2.91403e-008 C

Thus, Capacitance = $\frac{Q}{V} = \frac{2.91409e-008}{10}$ = 2.914nF

C/m $= \frac{2.914nF}{14m}$ = 207.1pF/m

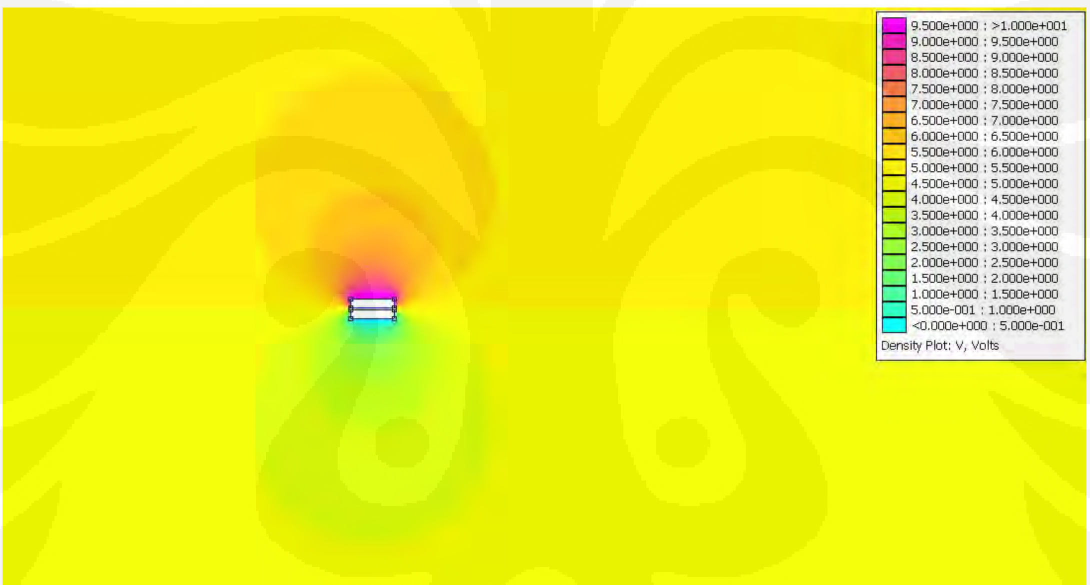
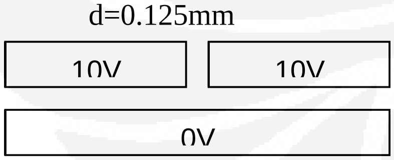


Figure 33 Total Voltage Intensity

b. d=0.125mm



D = 0.5mm

The 2 upper plates sized refer to the previous simulation, however the bottom plate is doubled size from the upper one for the length. Results:

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	Voltage (V)	Q (Coulombs)
Upper Plate 1	10V	2.3133e-08 C
Upper Plate 2	10V	2.7286e-008 C
Bottom Plate	0V	-5.45575e-008 C

Thus the capacitances:

$$C_{\text{upper plate 1}}/\text{m} = \left(\frac{Q1}{V}\right)\Big/ m = \frac{2.3133e-08}{10}/14m = 165.235\text{pF/m}$$

$$C_{\text{upper plate 2}}/\text{m} = \left(\frac{Q2}{V}\right)\Big/ m = \frac{2.73133e-08}{10}/14m = 198.06\text{pF/m}$$

$$C_{\text{total}}/\text{m} = \left(\frac{Q1+Q2}{V}\right)\Big/ m = \frac{(2.3133+2.73133)e-08}{10}/14m = 395.9\text{pF/m}$$

$$\mathbf{C_{\text{upper plate 1}}/m + C_{\text{upper plate 2}}/m \approx C_{\text{total}}/m}$$

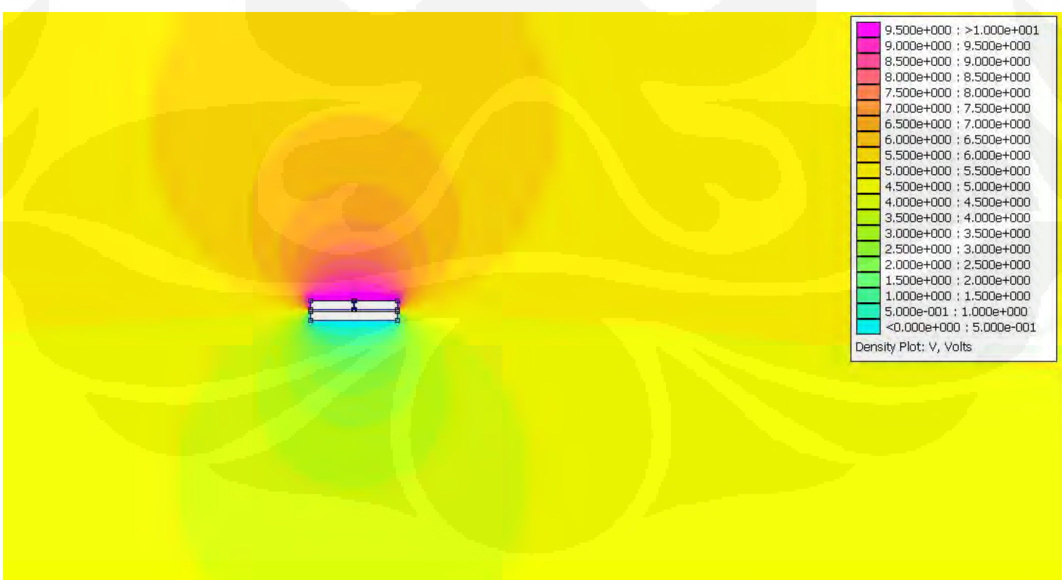

Figure 34 Total Voltage Intensity

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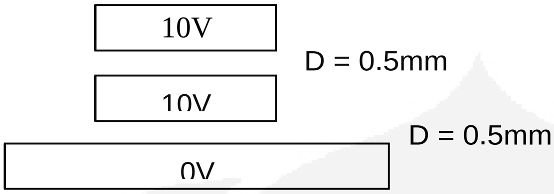
c.



With the same configuration sizes as before, results:

	Voltage (V)	Q (Coulombs)
Upper Plate	10V	0.244475e-08 C
Middle Plate	10V	2.897986e-008 C
Bottom Plate	0V	-3.29107e-008 C

$$C_{\text{upper plate}}/m = \left(\frac{Q1}{V}\right)\Big/ m = \frac{0.244475e-08}{0}/14m = 0\text{pF/m}$$

$$C_{\text{middle plate}}/m = \left(\frac{Q2}{V}\right)\Big/ m = \frac{2.897986e-08}{10}/14m = 210.15\text{pF/m}$$

$$C_{\text{total}}/m = \left(\frac{Q1+Q2}{V}\right)\Big/ m = \frac{(0.244475+2.89798)e-08}{10}/14m = 224.46\text{pF/m}$$

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Figure 35 Total Voltage Intensity

For the first set of simulation, it determines when two plates of conductors applied a step voltage, both conductors will have same and opposite Q charge value. Where it can be determined furthermore for another arrangement, for instance two identical conductors arranged horizontally with one conductor doubled size from the other conductors placed up side down will have the accumulative Q value same as the bigger bottom conductor with opposite sign.

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4.2.2 Simulation Set 2

For all the simulation sets 2, consist of four conductors with different shape and sizes. The similarity between them is where conductor 1 and 2 (the 2 top) conductors will be applied with 10V) and 3 and 4 (the 2 below) conductors act with 0V. Conductor 1 will further called as FAR conductor, while conductor 2 as NEAR conductor. The simulation arranged with varies d (space between conductor 1 and 2 as well as 3 and 4) and D (space between conductor 2 and 3). Spacing for d are made in range 1mm to 10mm, in other hand D spacing made between 50mm to 1000mm. Voltage 10V applied to conductor 1 and 2, and 0V to conductor 3 and 4.

a. The simulation consists of conductors sized 10mmx10mm

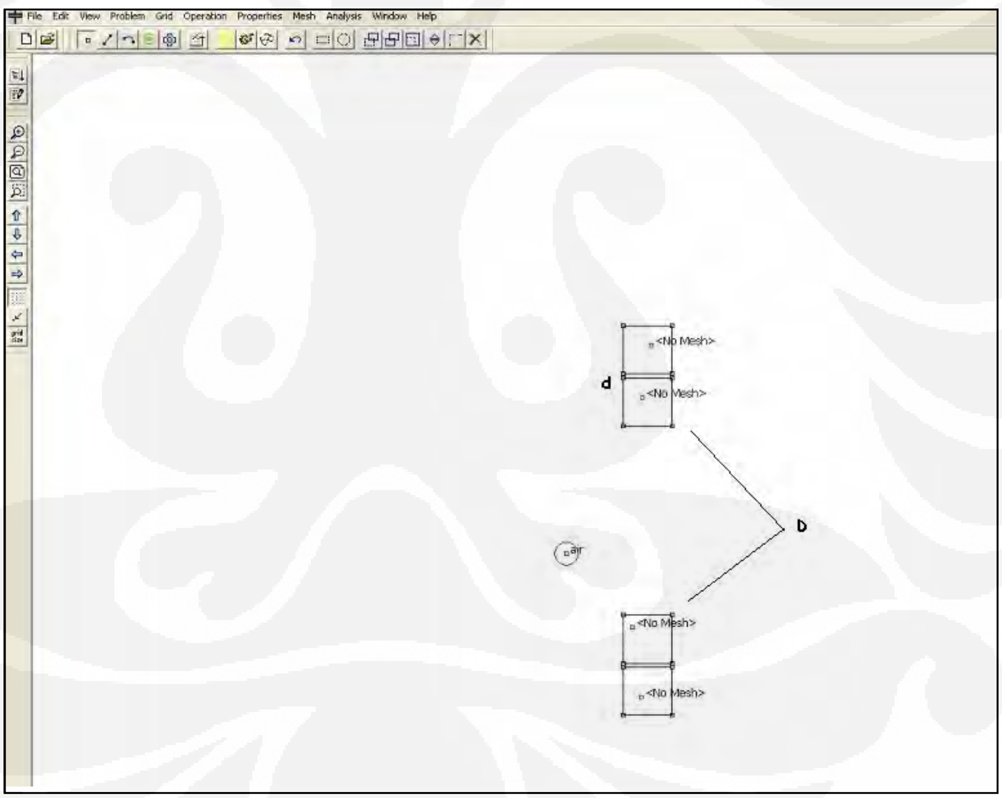

Figure 36 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) and 2 (NEAR conductor) (Appendix A) are illustrated in graphs below. The highest capacitance along FAR conductor gotten for arrangement d=10mm, D=50mm for 6.27059pF/m. Match with the FAR conductor, NEAR conductor highest capacitance captured at those arrangement at 10.08420pF/m.

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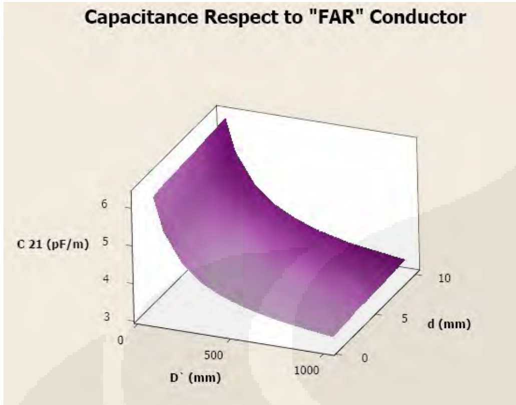

Figure 37 Capacitance of "FAR" Conductor

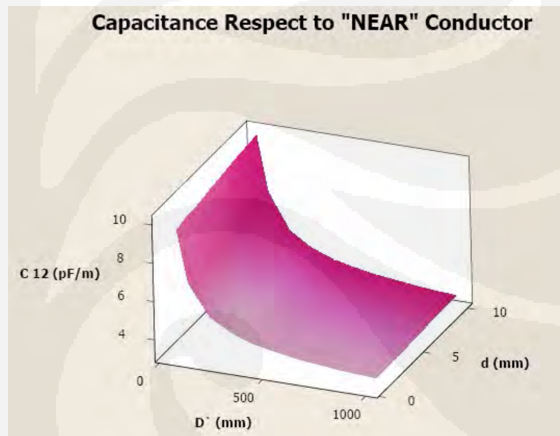

Figure 38 Capacitance of "NEAR" Conductor

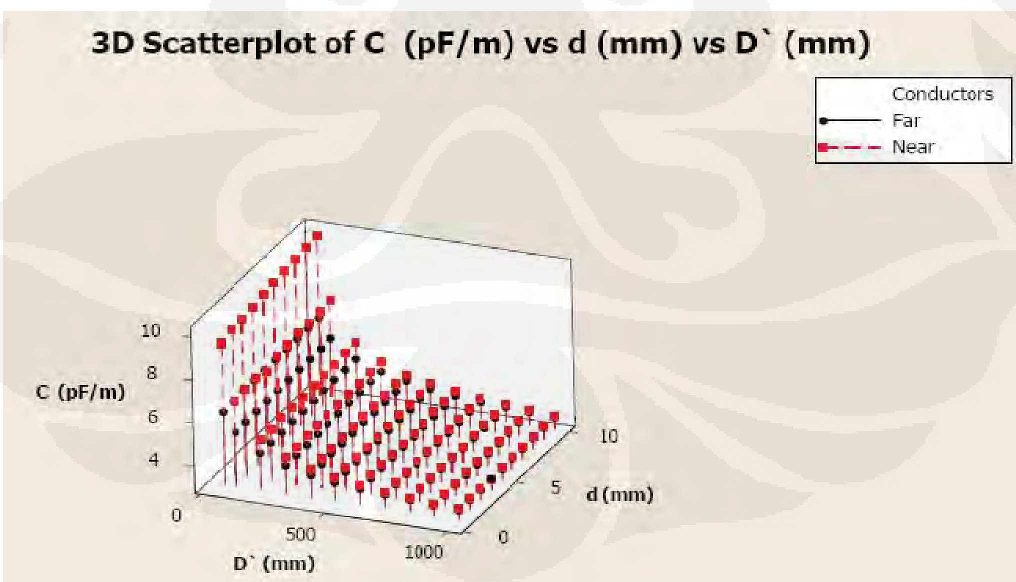

Figure 39 Capacitance Comparison of Both Conductors

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b. The simulation combining 10x10mm conductors with the doubled area size, 20mmx10mm conductors.

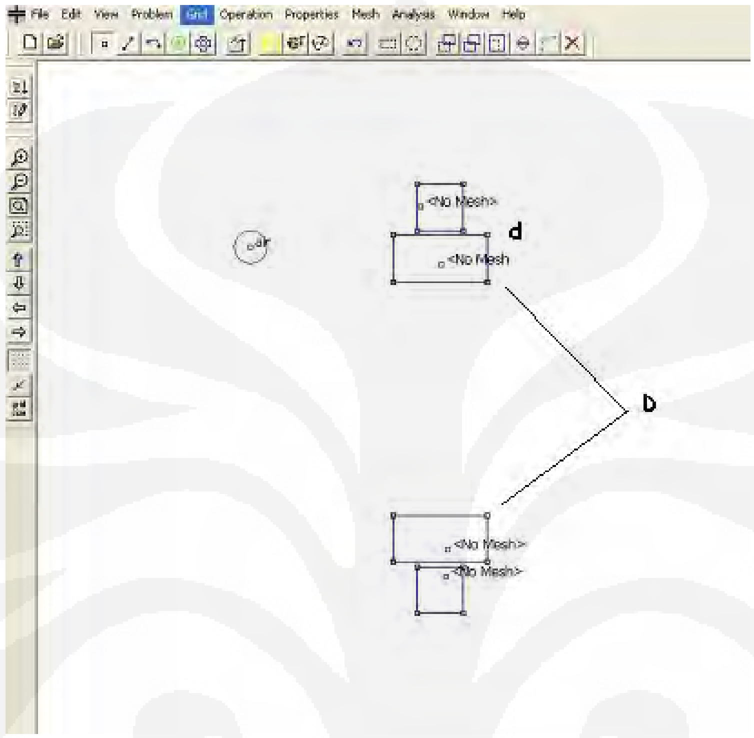

Figure 40 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) and 2 (NEAR conductor) (Appendix B) are illustrated in graphs below. The highest capacitance along FAR conductor gotten for arrangement d=10mm, D=50mm for 5.10485pF/m. Match with the FAR conductor, NEAR conductor highest capacitance captured at those arrangement at 11.731pF/m.

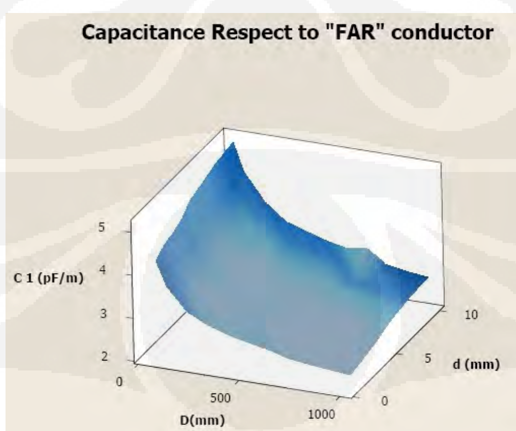

Figure 41 Capacitance of "FAR" Conductor

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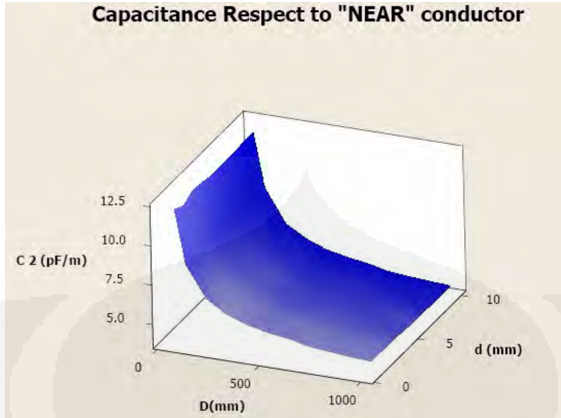

Figure 42 Capacitance of "NEAR" Conductor

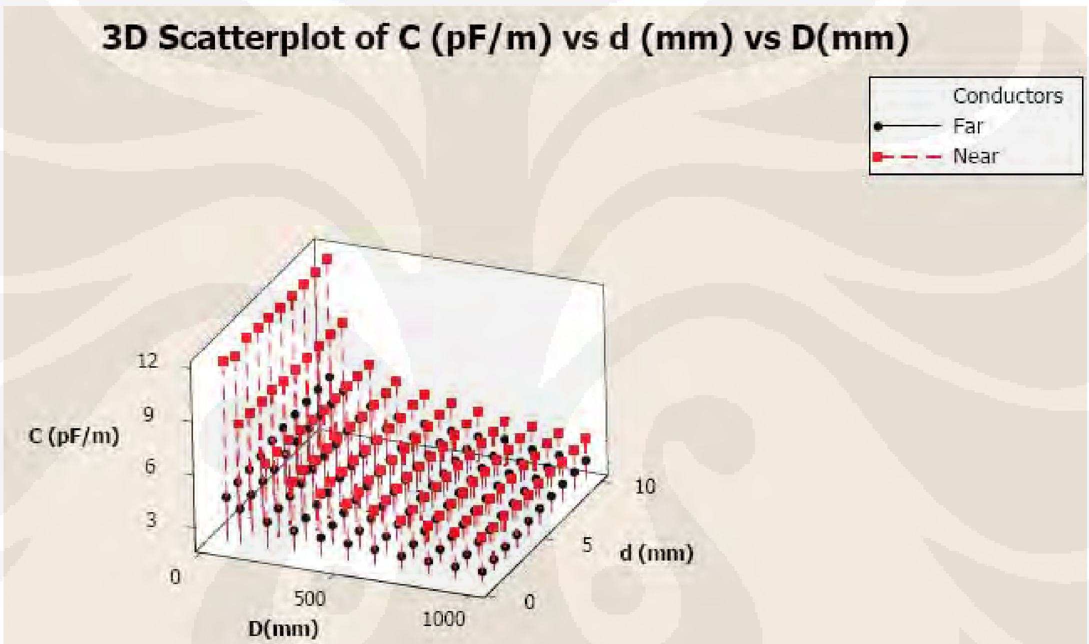

Figure 43 Capacitance Comparison of Both Conductors

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c. The simulation use the 20mmx10mm conductors

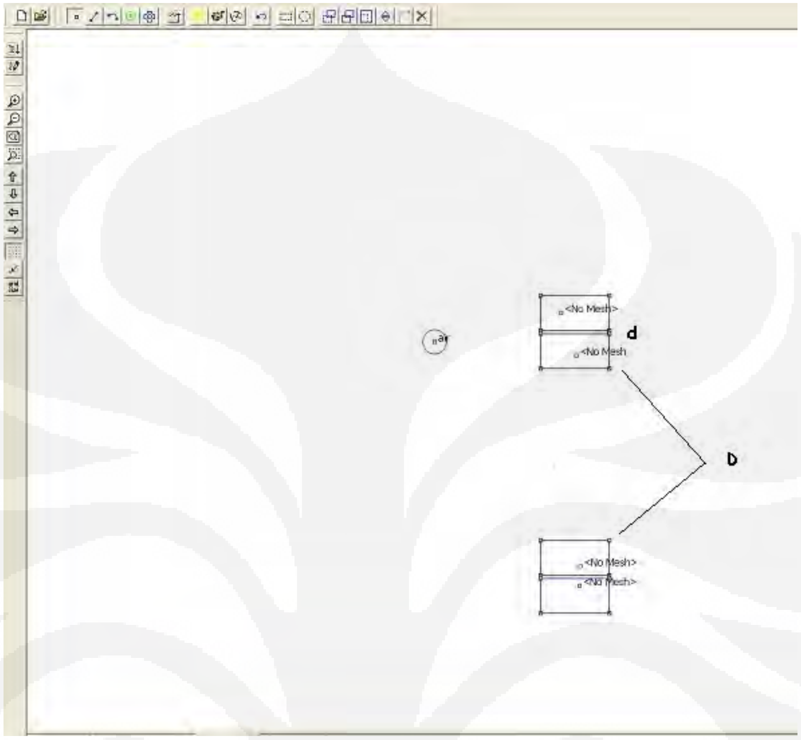

Figure 44 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) and 2 (NEAR conductor) (Appendix C) are illustrated in graphs below. The highest capacitance along FAR conductor gotten for arrangement d=10mm, D=50mm for 6.48079pF/m. Match with the FAR conductor, NEAR conductor highest capacitance captured at those arrangement at 10.9711pF/m.

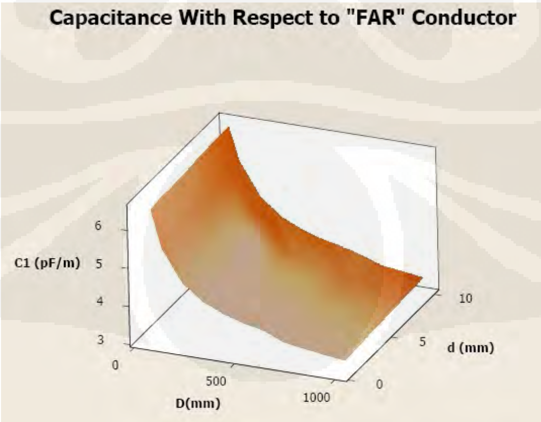

Figure 45 Capacitance of “FAR” Conductor

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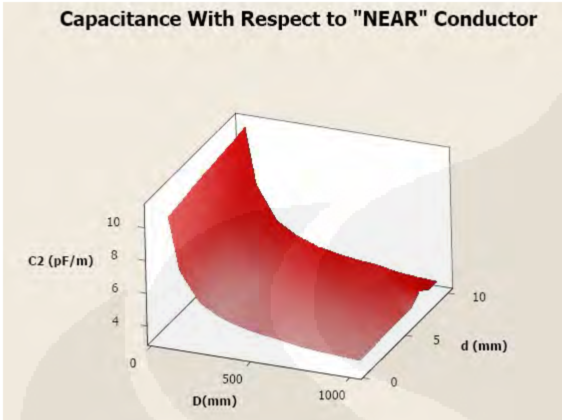

Figure 46 Capacitance of "NEAR" Conductor

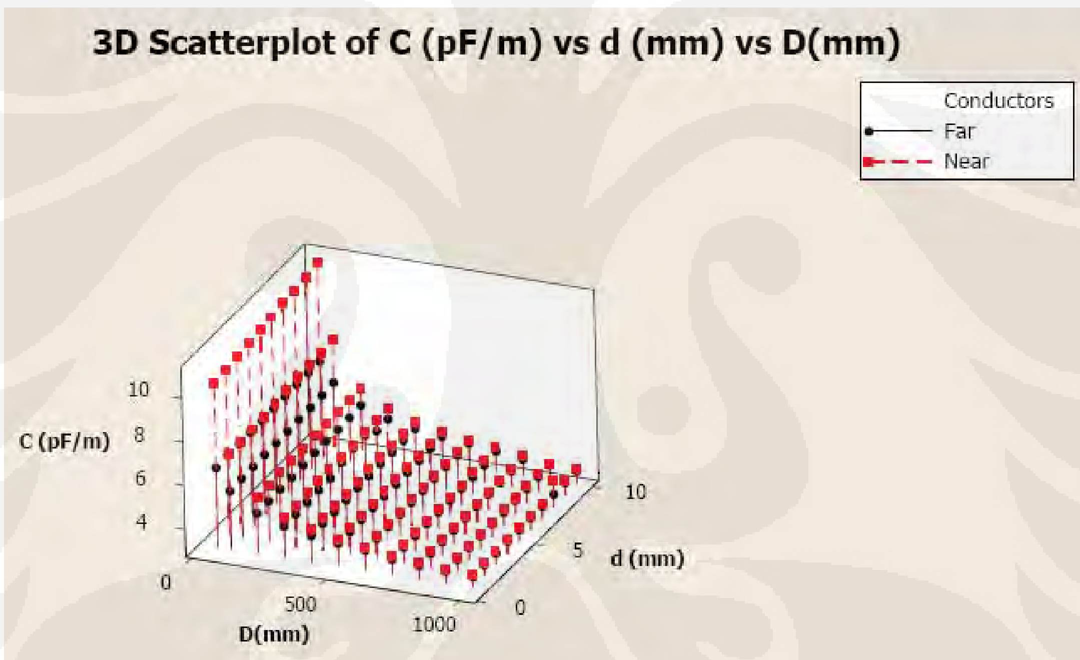

Figure 47 Capacitance Comparison of Both Conductors

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4.2.3 Simulation Set 3

The third simulation set forms conductors with fix d=1mm and vary D between 50mm to 1000mm. Voltage 10V applied to conductor 1 and 2 (FAR and NEAR), and 0V to conductor 3 and 4.

a. FAR conductor and number 4 are sized 10mmx10mm. NEAR conductor and the 3 rd conductors are sized 32mmx10mm

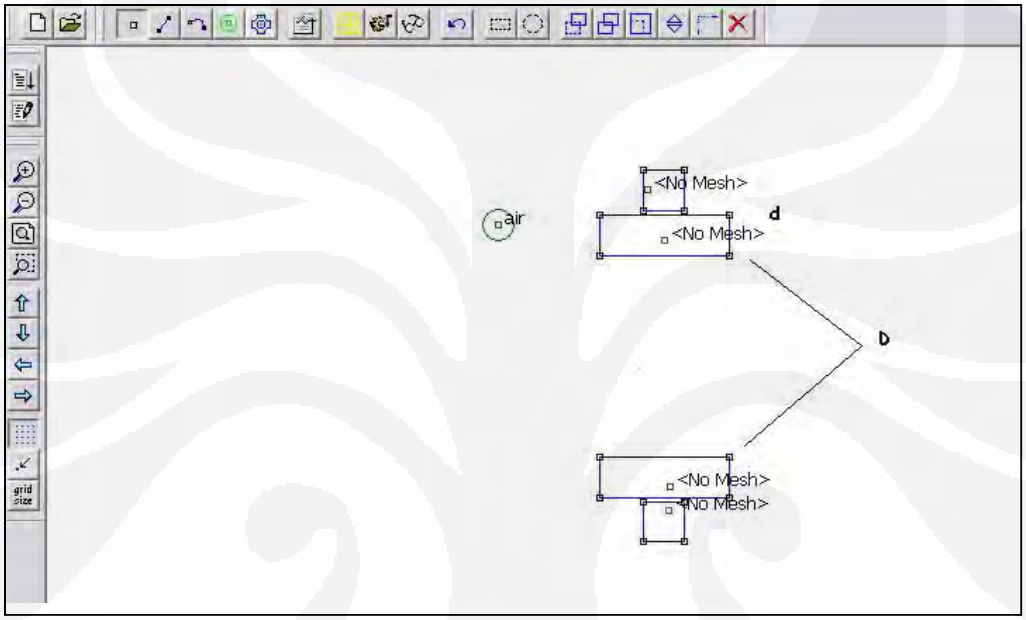

Figure 48 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) and 2 (NEAR conductor) (Appendix D) are illustrated in graphs below. The highest capacitance along FAR conductor gotten for arrangement D=50mm for 3.219pF/m. Match with the FAR conductor, NEAR conductor highest capacitance captured at D=50mm arrangement at 14.989pF/m.

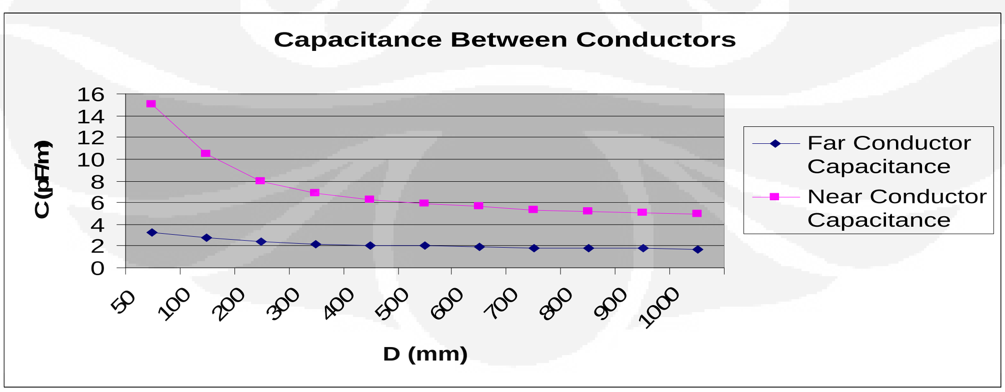

Figure 49 Capacitance of Both Conductors

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b. The simulation form a conductor size 10mmx10mm 3 quarter surrounded by U shape conductor that has 32mm in width and 10mm in each small width (x, y, and z). The total height is 21mm.

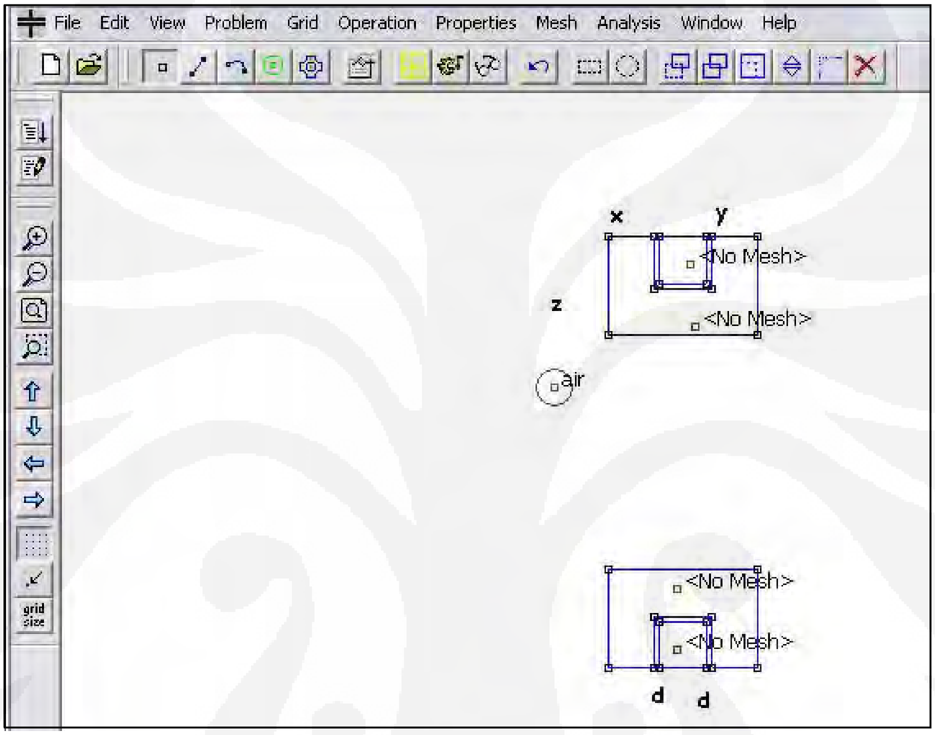

Figure 50 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) and 2 (NEAR conductor) (Appendix E) are illustrated in graphs below. The highest capacitance along FAR conductor gotten for arrangement D=50mm for 0.820587pF/m. Match with the FAR conductor, NEAR conductor highest capacitance captured at D=50mm arrangement at 18.1977pF/m.

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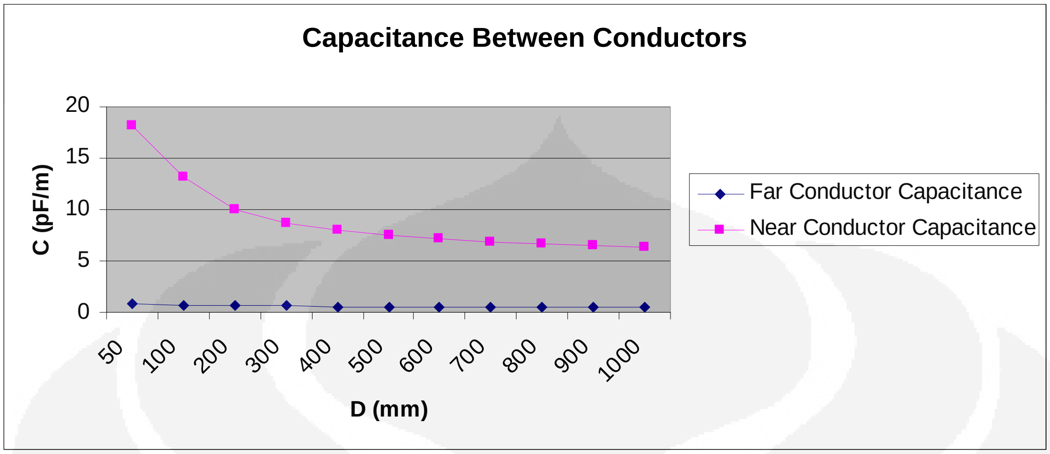

Figure 51 Capacitance of Both Conductors

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4.2.4 Simulation Set 4

10mmx10mm conductors from the previous simulation now are nearly surrounded until fully surrounded by O-shape conductor that has 32mmx22mm. Distance surrounds inner conductor to the outer is 1mm. The outer conductors vary from slightly closed to fully closed condition to see how it affects the inner conductor capacitance. The gap of the closing outer conductor differs from 0mm, 1mm and 5mm. D (distance between top to bottom conductors are 50 mm and 1000mm. The top inner conductor will be called C1 and C2 is for outer top conductor.

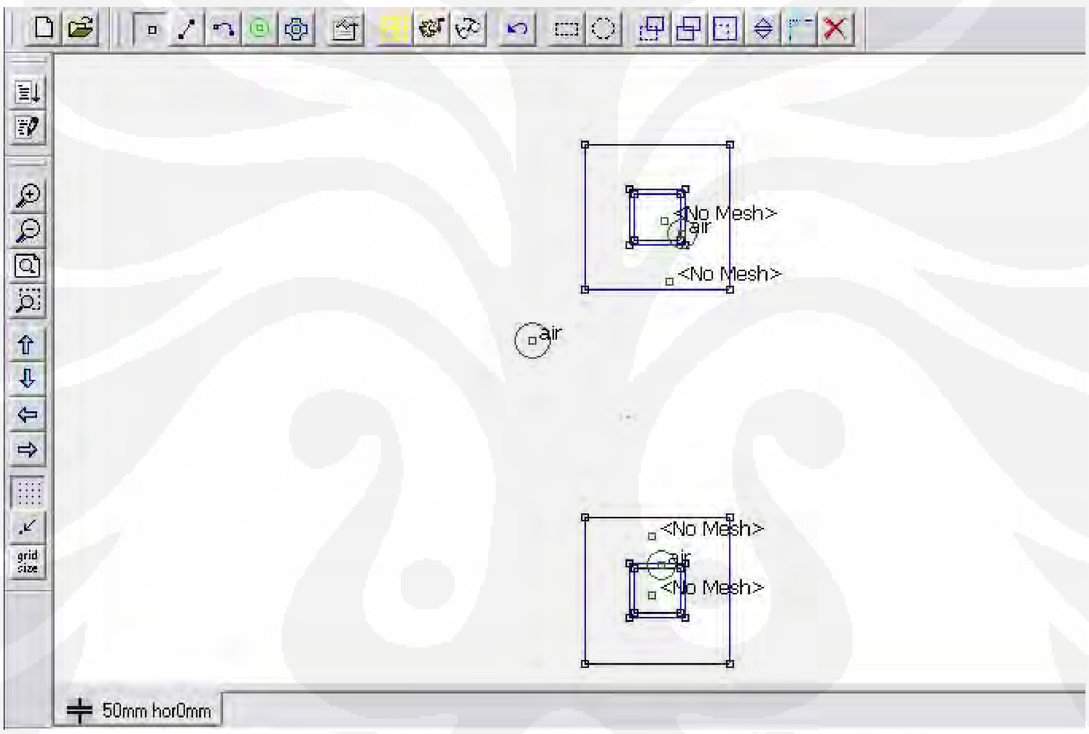

Figure 52 Conductors Arrangement

D = 50mm

d (mm)	C1 (pF/m)	C2 (pF/m)
5	-2.10567e-25	20.1198
1	-5.09867e-28	20.1181
0	0	20.1157

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D = 1000mm

d (mm)	C1 (pF/m)	C2 (pF/m)
5	-2.78909e-22	7.1679
1	-1.98977e-24	7.17153
0	0	7.16818

From the facts taken, the (-) capacitances can be assumed as 0 (zero) capacitance because the value is multiplied to a very large 10 to the power minus number, until the outer conductor is closed perfectly and reaches the exact zero capacitance. It shows that a surrounded conductor plate will not have any capacitance value.

4.2.5 Simulation Set 5

For all the fifth simulation sets, consist of four conductors with different shapes and sizes. The similarity between them is where conductor 1 and 2 (the 2 top) conductors will be applied with 10V) and 3 and 4 (the 2 below) conductors act with 0V. Conductor 1 will further called as FAR conductor, while conductor 2 as NEAR conductor. The simulation arranged with fixed d=1mm and D=100mm.

a. 10mmx10mm and 20mmx5mm conductors to get same area size conductors.

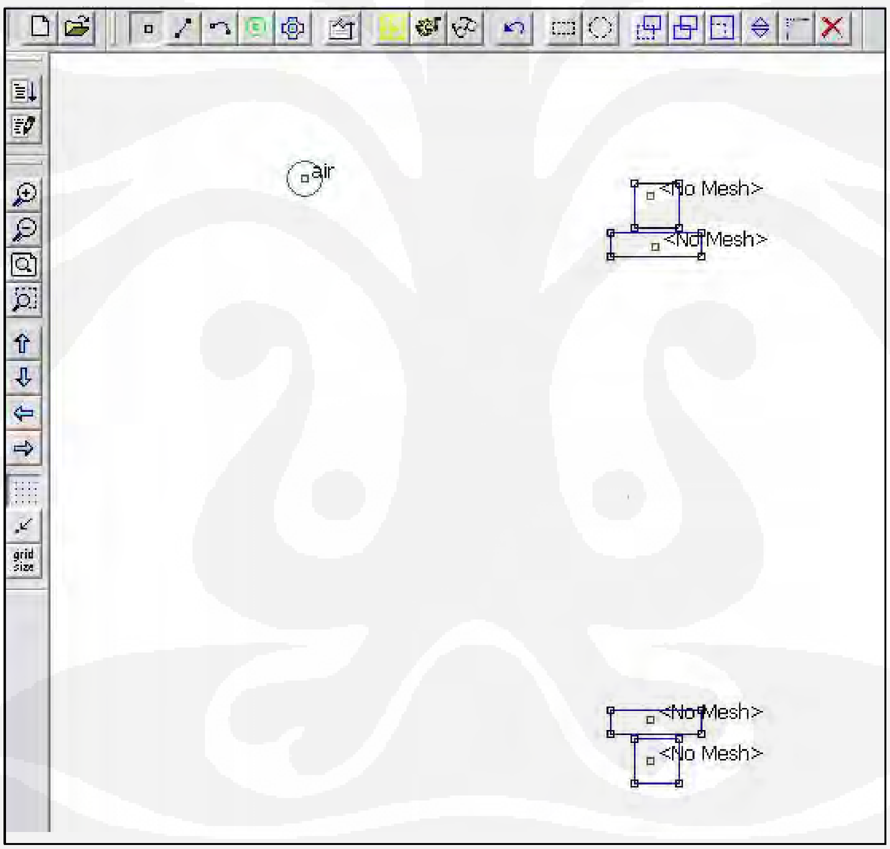

Figure 53 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) measured 3.84939pF/m while 7.64617pF/m is recorded for the NEAR conductor capacitance.

Establishment of current..., Balqis Ramasari Nursofinia, FT UI, 2008

a. 10mmx10mm conductors combined with the same area size U-shape conductors.

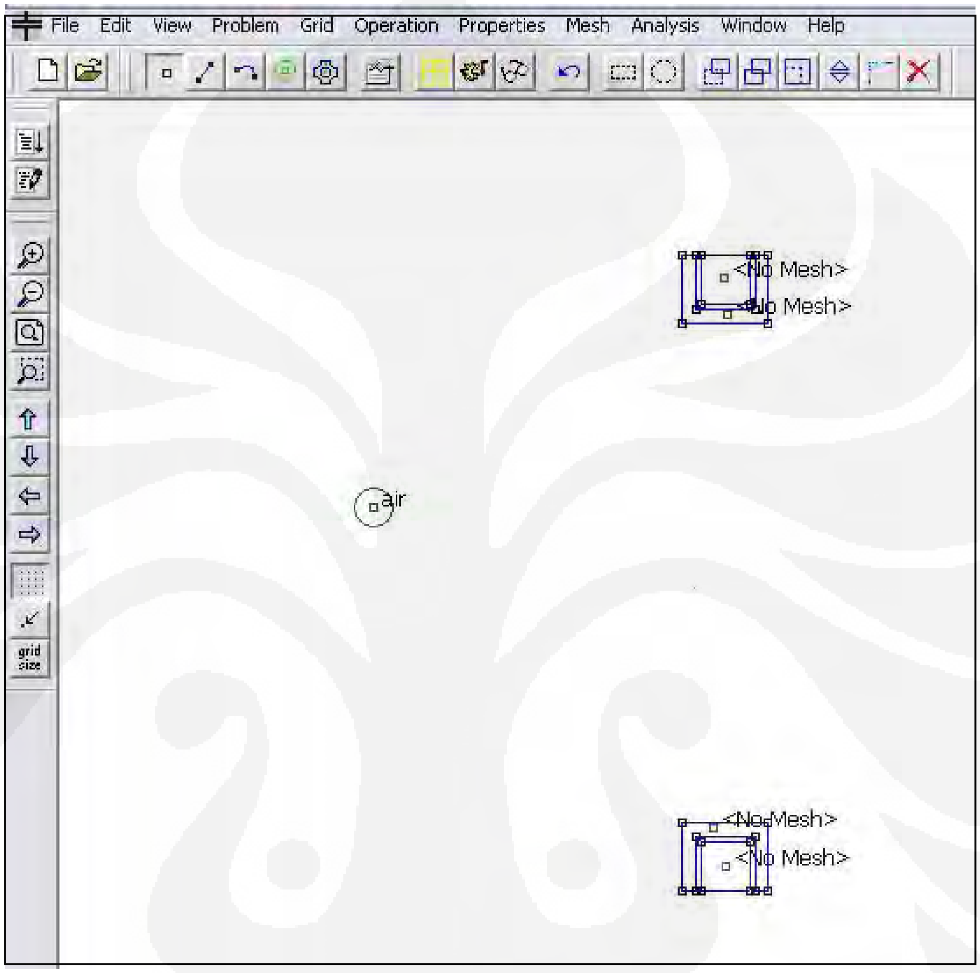

Figure 54 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) measured 1.22694pF/m while 10.0697pF/m is recorded for the NEAR conductor capacitance.

Establishment of current..., Balqis Ramasari Nursofinia, FT UI, 2008

b. The previous simulation modified in this simulation, thus the U-shape conductors extended to rectangular shape that sized 39.112mmx2.556mm in purpose to get the same area size as before.

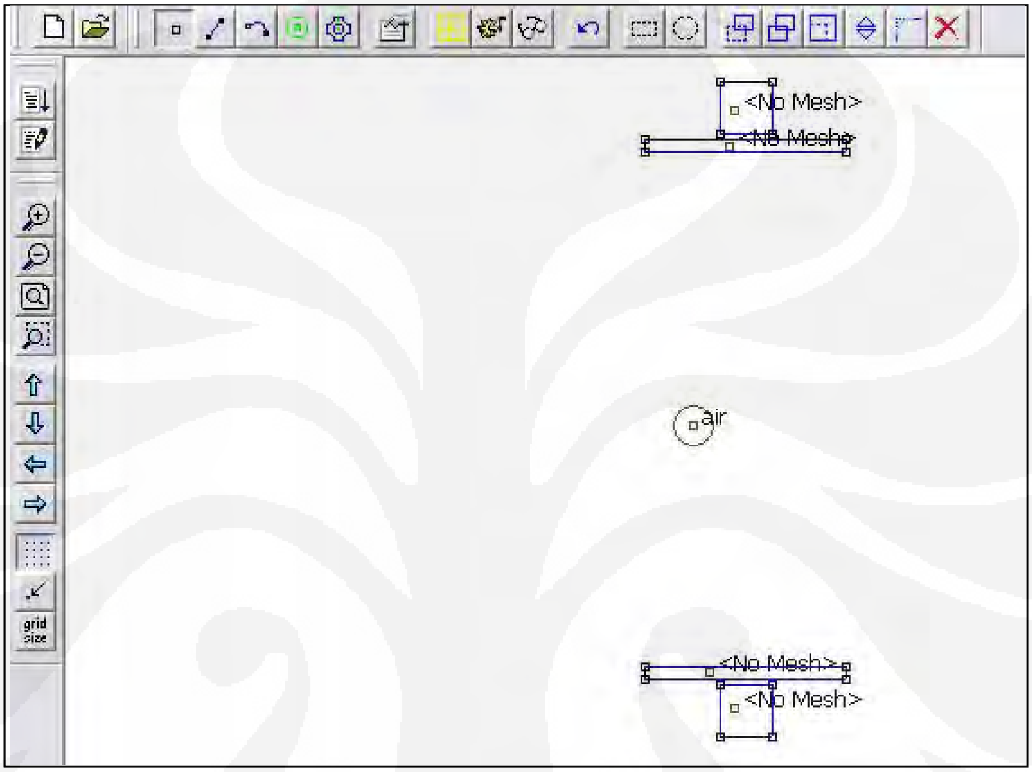

Figure 55 Conductors Arrangement

Capacitance results for conductor 1 (FAR conductor) measured 2.79256pF/m while 10.3754pF/m is recorded for the NEAR conductor capacitance.

Establishment of current..., Balqis Ramasari Nursofinia, FT UI, 2008

c. Two 10mmx10mm square shape conductors arranged horizontally mirrored with other two of them. The upper conductance that capacitance has been measured further called C1 for the left side and C2 for the right. d in this case is the distance between conductors horizontally.

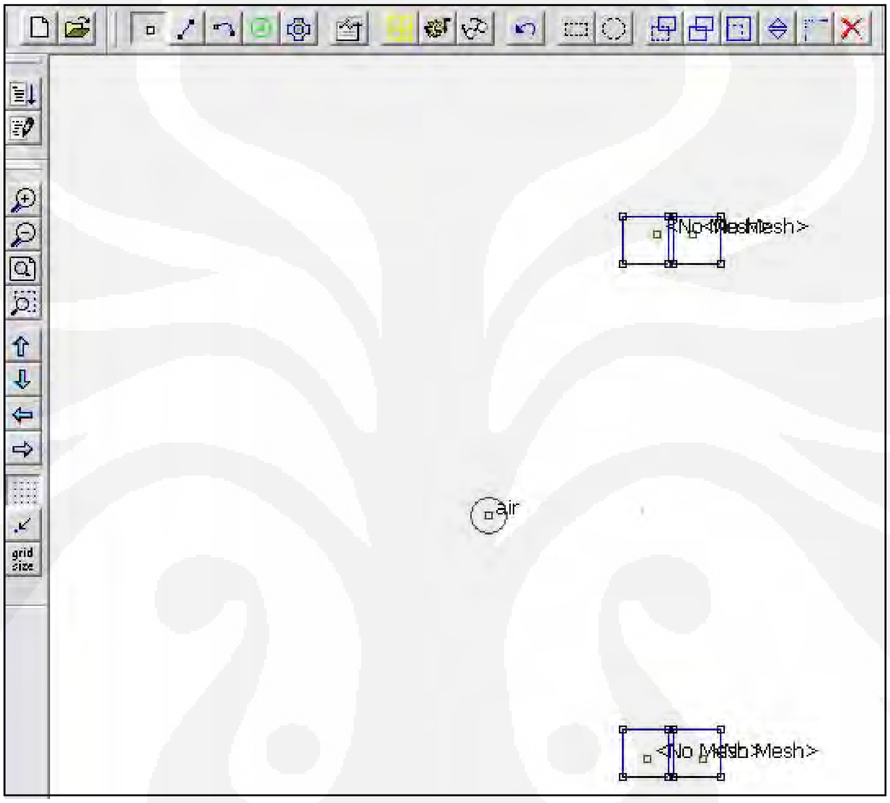

Figure 56 Conductors Arrangement

Capacitance results for C1 measured 5.7173pF/m while 5.7091pF/m is recorded for the C2 capacitance.

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d. Two 10mmx10mm square shape conductors arranged vertically mirrored with other two of them. The two upper conductance that capacitance has been measured further called C1 for the very top and C2 for the second top. d in this case is for the distance between conductors 1 and 2 as well as 3 and 4.

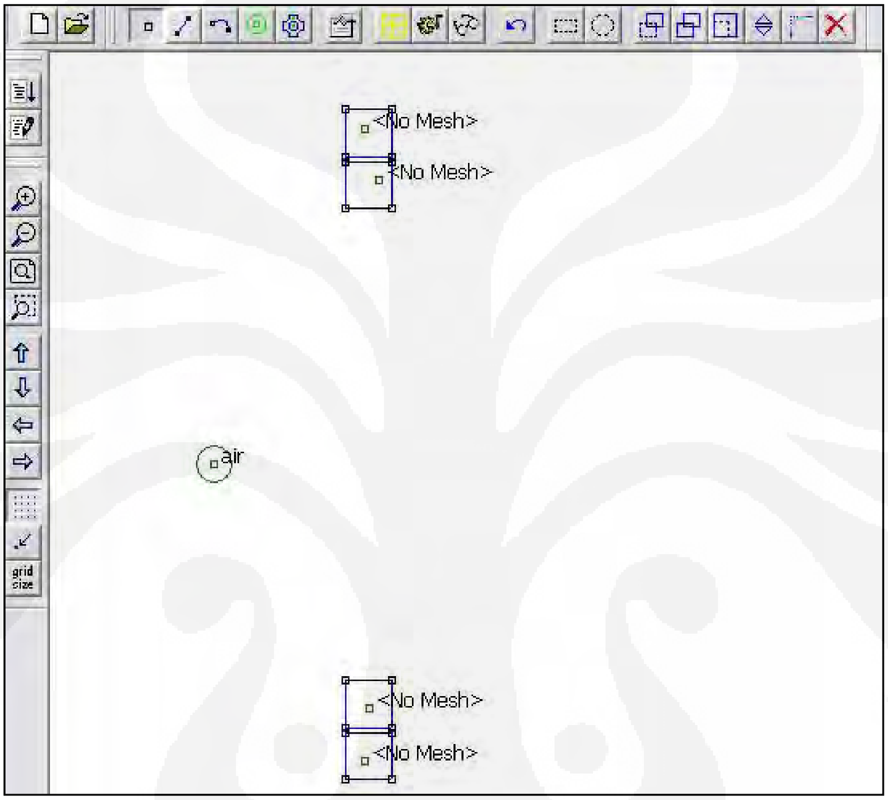

Figure 57 Conductors Arrangement

Capacitance results for C1 measured 4.98202pF/m while 6.07752pF/m is recorded for the C2 capacitance.

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5. Conclusions

It has been shown that displacement currents, electromagnetic propagation, and diffusion are the basic fundamentals for establishing current changes in conductors. Voltage or currents are initially applied on the surface of the conductor then gradually diffuse into the interior of conductors.

In conclusion it has been shown by the FEMM simulation that the charge values of any parallel conductors in vertical arrangements (up-side down) have the equal value with opposite signs for different voltage applied (e.g. one side for 10V and the other side is 0V). Accumulation is applied as well for more than two conductors used. It supports the theory that capacitance is affected by the voltage, electromagnetic propagation area of conductors and distance between conductors.

The laboratory experiment results show that the behaviour of parallel plate cable is quite the same during the charging and discharging state is quite accurate to the theory. However, the experiments failed in providing satisfying result of the behaviour of the capacitors. This is the effect of the circuit's inability to drive faster voltage into the capacitors.

It is necessary for future implementation of this project to upgrade the circuit, especially by changing the components so that the capacitor could be charged and discharged by faster voltage. The PCB of the circuit could also be upgraded by changing the size of the track to reduce the noise.

Establishment of current..., Balqis Ramasari Nursofinia, FT UI, 2008

6. References

J. Edwards, T.K. Saha, "Establishment of Current in Conductors", AUPEC 2003, Christchurch, New Zealand.

Matthew N.O.Sadiku, "Elements of Electromagnetic", International 4th Edition

J.Edwards, "Conduction and Displacement Currents in Capacitor", AUPEC 2004, Brisbane, Australia

Establishment of current..., Balqis Ramasari Nursofinia, FT UI, 2008

Appendix A Simulation Set 2.a Capacitance Result

	D	C1(pF/m)	C2(pF/m)	Bottom1(pF/m)	Bottom2(pF/m)
d=1	50	6.09805	9.29484	-9.29880	-6.09686
	100	5.23540	6.65952	-6.66369	-5.23267
	200	4.44776	5.06580	-5.06089	-4.45899
	300	4.03004	4.42379	-4.41382	-4.03784
	400	3.76924	4.03806	-4.03816	-3.76957
	500	3.59617	3.80044	-3.79700	-3.59916
	600	3.47286	3.62693	-3.62696	-3.47334
	700	3.36270	3.49703	-3.49539	-3.36645
	800	3.28497	3.38336	-3.39057	-3.28169
	900	3.21227	3.29935	-3.30611	-3.20758
	1000	3.15067	3.22794	-3.23146	-3.15019
d=2	D				
	50	6.14706	9.46434	-9.48111	-6.12599
	100	5.24506	6.76914	-6.77694	-5.23744
	200	4.47041	5.11022	-5.12874	-4.45003
	300	4.04899	4.45497	-4.45367	-4.05068
	400	3.81539	4.07578	-4.07615	-3.81561
	500	3.62932	3.82803	-3.82837	-3.62954
	600	3.48238	3.65023	-3.65044	-3.48281
	700	3.39191	3.50448	-3.51837	-3.37545
	800	3.30118	3.40738	-3.41079	-3.29165
	900	3.22128	3.33155	-3.32778	-3.22562
	1000	3.17077	3.25443	-3.25517	-3.17412

	D				
	50	6.17459	9.47455	-9.48161	-6.16520
	100	5.28304	6.81418	-6.82463	-5.27439
	200	4.47607	5.15555	-5.14745	-4.48327
	300	4.06039	4.49264	-4.47961	-4.07678
	400	3.82668	4.09102	-4.09114	-3.82688
d=3	500	3.64228	3.85400	-3.85351	-3.64287
	600	3.50180	3.66860	-3.66843	-3.50222
	700	3.41277	3.51689	-3.52647	-3.39916
	800	3.31205	3.42873	-3.40908	-3.32991
	900	3.24313	3.34375	-3.34717	-3.23858
	1000	3.18457	3.26890	-3.27966	-3.17784
	D				
	50	6.17272	9.58421	-9.58401	-6.16787
	100	5.29832	6.68767	-6.87077	-5.29536
	200	4.50288	5.18270	-5.19062	-4.49716
	300	4.10381	4.51909	-4.51901	-4.10395
	400	3.83200	4.14041	-4.14283	-3.82955
d=4	500	3.65794	3.87466	-3.87703	-3.65814
	600	3.51791	3.70058	-3.70136	-3.51772
	700	3.40052	3.55916	-3.53148	-3.39954
	800	3.32904	3.44245	-3.44612	-3.32711
	900	3.24834	3.36513	-3.35707	-3.25378
	1000	3.24206	3.24053	-3.27975	-3.20707

	D				
d=5	50	6.19162	9.69172	-9.70095	-6.18588
	100	5.32134	6.91634	-6.90927	-5.33180
	200	4.52813	5.22114	-5.23547	-4.51632
	300	4.12029	4.53063	-4.52635	-4.12707
	400	3.85827	4.14869	-4.15459	-3.85075
	500	3.67922	3.89401	-3.89506	-3.67890
	600	3.54427	3.70237	-3.70277	-3.54474
	700	3.42969	3.57097	-3.57114	-3.43331
	800	3.34712	3.46138	-3.46503	-3.34219
	900	3.26030	3.38788	-3.38254	-3.26051
	1000	3.21051	3.29930	-3.21803	-3.21803
	D				
d=6	50	6.19711	9.77958	-9.75377	-6.21219
	100	5.33542	6.97498	-6.96678	-5.34850
	200	4.54747	5.25151	-5.24671	-4.55742
	300	4.13315	4.56232	-4.57447	-4.12148
	400	3.88993	4.16737	-4.18175	-3.87064
	500	3.69473	3.91147	-3.92480	-3.68819
	600	3.55772	3.72341	-3.71884	-3.56320
	700	3.44892	3.58632	-3.58291	-3.45187
	800	3.35962	3.47665	-3.48262	-3.35354
	900	3.29035	3.38379	-3.39009	-3.28128
	1000	3.23127	3.30614	-3.31795	-3.22739

	D				
d=7	50	6.21928	9.87385	-9.87450	-6.22749
	100	5.37140	7.05575	-7.00036	-5.45530
	200	4.56768	5.29065	-5.29688	-4.55880
	300	4.16557	4.58407	-4.59092	-4.15632
	400	3.87827	4.21518	-4.21515	-3.87875
	500	3.70691	3.93045	-3.93245	-3.70504
	600	3.57651	3.74261	-3.74419	-3.57561
	700	3.45250	3.61157	-3.60630	-3.45631
	800	3.38203	3.48925	-3.50280	-3.37345
	900	3.30582	3.40284	-3.41184	-3.30023
	1000	3.23001	3.33792	-3.34066	-3.23272
	D				
d=8	50	6.24147	9.96438	-9.98446	-6.22360
	100	5.38363	7.07286	-7.09731	-5.36551
	200	4.58176	5.32827	-5.34150	-4.57341
	300	4.18483	4.61364	-4.62343	-4.17336
	400	3.89541	4.24315	-4.24118	-3.89828
	500	3.71724	3.96838	-3.96726	-3.71834
	600	3.57948	3.77587	-3.77567	-3.58272
	700	3.46469	3.63759	-3.63249	-3.47130
	800	3.38585	3.51813	-3.52509	-3.38329
	900	3.31264	3.42425	-3.43260	-3.30509
	1000	3.25200	3.34685	-3.34379	-3.25978

	D				
d=9	50	6.25476	10.02120	-10.02510	-6.24912
	100	5.39504	7.13717	-7.14511	-5.38727
	200	4.59154	5.38160	-5.37301	-4.60336
	300	4.19177	4.64964	-4.66579	-4.18026
	400	3.91703	4.26312	-4.26515	-3.91486
	500	3.73514	3.98668	-3.99512	-3.72731
	600	3.58796	3.80737	-3.79785	-3.59129
	700	3.48412	3.65070	-3.64941	-3.48760
	800	3.40049	3.53546	-3.52811	-3.41079
	900	3.33318	3.43474	-3.42579	-3.33863
	1000	3.27070	3.35641	-3.35551	-3.27823
	D				
d=10	50	6.27059	10.08420	-10.08590	-6.26533
	100	5.41255	7.21462	-7.18874	-5.43096
	200	4.63295	5.38812	-5.40060	-4.62428
	300	4.21356	4.67697	-4.68694	-4.19712
	400	3.94658	4.26426	-4.26678	-3.94489
	500	3.74732	4.00668	-4.00327	-3.74572
	600	3.60969	3.80973	-3.81090	-3.60866
	700	3.48910	3.67796	-3.66683	-3.50402
	800	3.41958	3.54900	-3.56377	-3.40517
	900	3.34756	3.44443	-3.45629	-3.33630
	1000	3.28049	3.37922	-3.37627	-3.28440

Appendix B Simulation Set 2.b Capacitance Result

	D(mm)	C1 (pF/m)	C2 (pF/m)
d = 1	50	4.15069	11.82920
	100	3.60513	8.44383
	200	3.08377	6.43994
	300	2.85494	5.63203
	400	2.69686	5.18759
	500	2.59113	4.90778
	600	2.50126	4.73621
	700	2.36806	4.44175
	800	2.30831	4.31202
	900	2.26067	4.20558
	1000	2.21626	4.12416
d = 2	50	4.32663	11.47110
	100	3.73717	8.39602
	200	3.21015	6.37998
	300	2.91936	5.61208
	400	2.74884	5.17132
	500	2.67345	4.86787
	600	2.59927	4.67186
	700	2.41225	4.42835
	800	2.34984	4.30120
	900	2.30167	4.19168
	1000	2.26044	4.10533

d = 3	50	4.39659	11.81940
	100	3.84065	8.37794
	200	3.24497	6.41573
	300	3.00528	5.58278
	400	2.81907	5.15488
	500	2.72216	4.86099
	600	2.63159	4.68291
	700	2.49674	4.40940
	800	2.41626	4.27400
	900	2.35916	4.17258
	1000	2.32466	4.08047
d = 4	50	4.51264	11.77900
	100	3.86441	8.41169
	200	3.33684	6.37443
	300	3.06892	5.57238
	400	2.89310	5.13644
	500	2.77972	4.84402
	600	2.70125	4.65500
	700	2.54301	4.37714
	800	2.47108	4.25259
	900	2.42320	4.14142
	1000	2.37700	4.05741

	50	4.74644	11.66100
	100	4.10033	8.24281
	200	3.50537	6.25050
	300	3.23246	5.44470
	400	3.01017	5.04308
d = 5	500	2.93240	4.73215
	600	2.83494	4.55834
	700	2.64344	4.29835
	800	2.57840	4.16613
	900	2.54218	4.04240
	1000	2.48033	3.97070
	50	4.83097	11.62560
	100	4.17031	8.25450
	200	3.58114	6.23317
	300	3.27942	5.45390
	400	3.10378	5.00401
d = 6	500	2.98920	4.71628
	600	2.88516	4.53911
	700	2.72033	4.26449
	800	2.64313	4.14235
	900	2.59465	4.03098
	1000	2.54555	3.94415

	50	4.92160	11.63890
	100	4.27764	8.24613
	200	3.62540	6.22576
	300	3.31445	5.44762
	400	3.18598	4.99200
d = 7	500	3.02670	4.69011
	600	2.90364	4.45899
	700	2.78425	4.19728
	800	2.69863	4.12356
	900	2.64511	4.09865
	1000	2.59635	3.92472
	50	5.00685	11.65790
	100	4.33562	8.23045
	200	3.72102	6.20217
	300	3.39763	5.41062
	400	3.21954	4.96435
d = 8	500	3.08904	4.69019
	600	2.99259	4.49474
	700	2.81366	4.22742
	800	2.74658	4.09352
	900	2.68848	3.98880
	1000	2.63707	3.90560

d = 9	50	5.05685	11.70770
	100	4.35480	8.30095
	200	3.77559	6.20136
	300	3.43654	5.41679
	400	3.23389	4.99321
	500	3.10564	4.69734
	600	3.00316	4.49474
	700	2.83562	4.23492
	800	2.75153	4.11837
	900	2.69674	4.00861
	1000	2.65475	3.91247
d = 10	50	5.10485	11.73100
	100	4.44355	8.28097
	200	3.82342	6.20547
	300	3.45522	5.45089
	400	3.29674	4.96467
	500	3.15080	4.69612
	600	3.05007	4.50831
	700	3.13064	4.20295
	800	2.80813	4.09280
	900	2.72780	4.00444
	1000	2.67140	3.92431

Appendix C Simulation Set 2.c Capacitance Result

	D (mm)	C1 (pF/m)	C2 (pF/m)
d=1mm	50	6.32973	10.16
	100	5.37191	7.05522
	200	4.54868	5.25639
	300	4.14843	4.55873
	400	3.90536	4.17613
	500	3.73948	3.92733
	600	3.63342	3.76332
	700	3.40667	3.55004
	800	3.32297	3.43701
	900	3.24654	3.35538
	1000	3.18454	3.28119
d=2mm	50	6.3922	10.2512
	100	5.41095	7.08606
	200	4.57269	5.28943
	300	4.17542	4.58136
	400	3.93496	4.19765
	500	3.76835	3.96518
	600	3.646	3.79313
	700	3.41928	3.58208
	800	3.34707	3.45372
	900	3.26572	3.37109
	1000	3.20785	3.29729

d=3mm	50	6.37506	10.3657
	100	5.43087	7.16488
	200	4.59652	5.33772
	300	4.1937	4.61715
	400	3.94451	4.23386
	500	3.77831	3.99676
	600	3.66683	3.81519
	700	3.4388	3.59761
	800	3.3587	3.4803
	900	3.28358	3.39284
	1000	3.21901	3.32164
d=4mm	50	6.38288	10.4789
	100	5.45406	7.22245
	200	4.60727	5.37825
	300	4.22503	4.64375
	400	3.96483	4.257
	500	3.81197	3.99765
	600	3.7038	3.82881
	700	3.45552	3.60987
	800	3.36654	3.49864
	900	3.30001	3.40433
	1000	3.2387	3.33125

d=5mm	50	6.39309	10.5656
	100	5.46776	7.30918
	200	4.64981	5.42201
	300	4.23184	4.68515
	400	3.98329	4.28495
	500	3.8126	4.0412
	600	3.71168	3.85509
	700	3.47557	3.63415
	800	3.38589	3.50916
	900	3.3165	3.4262
	1000	3.24744	3.34802
d=6mm	50	6.43562	10.6127
	100	5.48923	7.3735
	200	4.68203	5.48732
	300	4.4472	4.711262
	400	4.01785	4.33126
	500	3.83752	4.06216
	600	3.72946	3.87115
	700	3.48521	3.65201
	800	3.40267	3.52416
	900	3.3275	3.4457
	1000	3.268	3.35929

d=7mm	50	6.45712	10.71823
	100	5.50321	7.4268
	200	4.6934	5.51623
	300	4.5813	4.74266
	400	4.035124	4.35781
	500	3.85267	4.08337
	600	3.75811	3.8964
	700	3.49664	3.6771
	800	3.42156	3.54673
	900	3.3389	3.458
	1000	3.28111	3.37413
d=8mm	50	6.46536	10.7759
	100	5.51725	7.48123
	200	4.70842	5.51765
	300	4.652278	4.77953
	400	4.04998	4.37624
	500	3.87113	4.1058
	600	3.77002	3.9072
	700	3.5068	3.69541
	800	3.4351	3.566
	900	3.3579	3.4763
	1000	3.2957	3.90128

d=9mm	50	6.47552	10.839
	100	5.55691	7.51034
	200	4.72368	5.55519
	300	4.3172	4.80089
	400	4.0641	4.39356
	500	3.89597	4.12454
	600	3.79069	3.93707
	700	3.5263	3.7168
	800	3.44653	3.5825
	900	3.36847	3.49809
	1000	3.31081	3.41249
d=10mm	50	6.48079	10.9711
	100	5.59586	7.55315
	200	4.76898	5.56179
	300	4.33738	4.83729
	400	4.08987	4.40741
	500	3.91386	4.14041
	600	3.80328	3.95725
	700	3.64366	3.85968
	800	3.46549	3.60402
	900	3.40013	3.48874
	1000	3.3264	3.42374

Appendix D Simulation Set 3.a Capacitance Result

D (mm)	C1 (pF/m)	C2 (pF/m)
50	3.219	14.989
100	2.82607	10.4627
200	2.3759	7.90438
300	2.19281	6.86439
400	2.07903	6.2951
500	2.02427	5.91502
600	1.96767	5.6702
700	1.83121	5.33806
800	1.78171	5.17785
900	1.76198	5.02561
1000	1.73262	4.91314

Appendix E Simulation Set 3.b Capacitance Result

D (mm)	C1 (pF/m)	C2 (pF/m)
50	0.820587	18.1977
100	0.731913	13.1275
200	0.642868	10.0091
300	0.59012	8.73843
400	0.550739	8.01364
500	0.525276	7.53308
600	0.507398	7.18287
700	0.493426	6.91065
800	0.477147	6.70703
900	0.467359	6.53791
1000	0.464303	6.3924

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