A DISSERTATION REPORT ON

"DESIGN AND DEVELOPMENT OF SOIL MOISTURE SENSOR BASED ON FREQUENCY DOMAIN REFLECTOMETRY TECHNIQUE"

by

ABHAY GUSAIN

(Roll No.: 208503)

Submitted in partial fulfilment of the requirement for the award of the degree of

MASTER OF TECHNOLOGY

IN

INSTRUMENTATION

Under the supervision and guidance of

INTERNAL SUPERVISOR:
Dr. S.K. MAHNA
Head and Professor
Deptt. of Physics
NIT KURUKSHETRA

EXTERNAL SUPERVISOR:
Mr. BABANKUMAR S BANSOD
Scientist-C, DU-1
Agrionics Department, CSIO
CHANDIGARH

DEPARTMENT OF PHYSICS

NATIONAL INSTITUTE OF TECHNOLOGY

INSTITUTE OF NATIONAL IMPORTANCE

KURUKSHETRA-136119

CENTRAL SCIENTIFIC INSTRUMENTS ORGANISATION

Sector 30 C, Chandigarh-160030

Phone: 0172 - 2656285/2657811/2657826; Ext: 462

Fax: 0172 - 2657267/2657082/2652651

E-mail : csiobabankumar@gmail.com

Ref. No.: CSIO/DU-1/AGRIONICS/Jan 2010 – Jun 2010

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CERTIFICATE

This is to certify that the project report entitled **"DESIGN AND DEVELOPMENT OF SOIL MOISTURE SENSOR BASED ON FREQUENCY DOMAIN REFLECTOMETRY TECHNIQUE"** being submitted to **NATIONAL INSTITUTE OF TECHNOLOGY KURUKSHETRA** for the degree of **MASTER OF TECHNOLOGY (Instrumentation)** is a bonafide work, done by **Mr. ABHAY GUSAIN (Roll No.208503)** under my guidance. The assistance and help received during this endeavour have been appropriately acknowledged. His performance during the whole period of thesis under my guidance was Outstanding.

13/07/2010

(Babankumar S Bansod)
Scientist-C, Agrionics (DU-1)
CSIO, Chandigarh.

Scientist
Central Scientific Instruments Organisation
Sector 30-C, Chandigarh - 160030

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(Dr. S.K. Mahna)
Head and Professor,
Deptt. of Physics,
NIT Kurukshetra.

DECLARATION

I hereby certify that the work which is being presented in this dissertation report entitled "**DESIGN AND DEVELOPMENT OF SOIL MOISTURE SENSOR BASED ON FREQUENCY DOMAIN REFLECTOMETRY TECHNIQUE**" in partial fulfilment of the requirement for the award of the degree of **MASTER OF TECHNOLOGY (Instrumentation)** submitted to the **NATIONAL INSTITUTE OF TECHNOLOGY KURUKSHETRA** is an authentic record of my own work under the supervision and guidance of **Mr. Babankumar S Bansod, Scientist-C, Central Scientific Instruments Organisation, Chandigarh.**

(Abhay Gusain)
Roll No.208503

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Babankumar S Bansod)
Scientist-C, Agrionics (DU-1),
CSIO, Chandigarh.

ABSTRACT

The FDR soil moisture sensor is a sensor which is used to measure the soil moisture content and is based on the principle of frequency domain reflectometry technique. The FDR soil moisture sensor system consists of a capacitive probe sensor and a Colpitts oscillator. The capacitive probe sensor consists of pair of parallel plate capacitors whose capacitance depends upon the dielectric constant of the soil and thus on the soil moisture content. The capacitive probe sensor is connected to the Colpitts oscillator which produces a sinusoidal signal whose frequency of oscillation depends upon the capacitance of the capacitive probe sensor and thus on the soil moisture content. The capacitive probe sensor is designed and simulated using the Integrated Electro software in order to determine the effects of the parameters like length, width, thickness and gap between the plates on the parameters like electric field, charge, capacitance, sensitivity and resolution of the probe sensor. The Colpitts oscillator is designed and simulated in the TINA Pro software to determine the effects of the various parameters like capacitance of the capacitive probe sensor, capacitance of the tank circuit and inductance of the tank circuit on the frequency of oscillation of the Colpitts oscillator. The capacitive probe sensor and the Colpitts oscillator are implemented in hardware and measurement of the soil moisture content of the soil samples prepared is done. A calibration equation between the soil moisture content and the capacitance of the capacitive probe sensor and between the frequency of oscillation of the Colpitts oscillator and the capacitance of the capacitive probe sensor is obtained. Thus the FDR soil moisture sensor is developed.

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CHAPTER 1

INTRODUCTION

1.1 TECHNOLOGY:-

FDR is a technique used in agrionics which utilizes the concept of frequency domain analysis to measure the content of soil moisture in any soil type. In FDR an oscillator is used to produce a pulse train (square wave) which is either fed in a capacitor(having varying capacitance) forming the part of probe sensor or the capacitor itself is a part of oscillator. The frequency of output signal of the oscillator varies with the capacitance of the capacitor which depends upon soil dielectric constant and thus on volumetric content of soil moisture[1][2]. This frequency is measured and the moisture content of the soil is determined from it.

1.2 GAPS IN EARLIER STUDIES:-

Frequency Domain Reflectometers is the technique that has been introduced recently. Previously TDR technique has been used for both cable testing purpose as well as for soil moisture determination but FDR has become the fastest and most accurate technique as compared to TDR technique. Frequency domain reflectometry (FDR) is rapidly gaining popularity in applications above 200MHz. Previously FDR techniques were used to test only transmission cables of any antenna system or in communication systems by generating an RF sweep that includes only the frequency range selected by the operator, allowing frequency-selective characteristics to be displayed clearly. Measurements include return loss (or standing wave ratio, SWR) vs. frequency and return loss (or SWR) vs. distance.

Recently FDR technique was introduced in the field of agrionics. The basic differences between the FDR sensors introduced are related to the use of the capacitive sensor used in the probe of the sensor system design. Previously the capacitive sensor was used as separate capacitor to which oscillating frequency signal was applied and subsequent changes in the output frequency of the capacitive sensor depends on the variation of capacitance of capacitive sensor and thus with the variation in soil dielectric constant or soil moisture.

The FDR sensor developed here uses the capacitor of probe sensor in different way. The capacitor of the capacitive sensor is used as a part of LC oscillator whose oscillation frequency varies with change in capacitance of capacitor which in turns depends upon the variation in soil dielectric constant or soil moisture.

1.3 OBJECTIVES:-

1. To study the various physical and chemical properties of soil.
2. To design and develop a soil moisture sensor system based on frequency domain reflectometry (FDR) technique.
3. To test the system for various soil types by carrying out the experiments and making detailed observations of the data obtained.
4. To analyse the data obtained in detail through various statistical techniques including software use for carrying out the data analysis.

1.4 METHODOLOGY OF ACHIEVING OBJECTIVES:-

The methodology includes following steps that are undertaken to achieve the objectives:-

1. Detailed study of the various properties- chemical and physical, of the soil and variation of these properties along with various soil types.
2. Detailed study of concept underlying the FDR technique.
3. Detailed study of the various design possibilities and implementing one of the design possibilities according to our system design specifications.
4. Design of the sensor system theoretically (on paper).
    - Calculation of design details of various components of the system.
    - Formulation of mathematical concepts underlying each component design detail.
5. Design of the sensor system virtually through simulation software used such as INTEGRATED ELECTRO, TINA PRO 7.0.
6. Realization and implementation of the system design in hardware.
7. Field work
    - Preparation of the soil samples.
    - Experiments on these samples and obtaining data from these samples through sensor system.

- Processing of data like mathematical computations to be done on data to determine the soil moisture and other parameters of interest.
- Analysis of the data through statistical techniques and comparison with that obtained by standard instrument.
- Drawing conclusions from the analysis of the data obtained.

1.5 Literature Survey:-

Frequency domain reflectometry is a technique that is used in agrionics utilizing the concept of frequency domain analysis to measure the content of soil moisture in any soil type. In FDR an oscillator is used to produce a pulse train which is either fed in a capacitor(having varying capacitance) forming the part of probe sensor or the capacitor itself is a part of oscillator. The frequency of output signal of the oscillator varies with the capacitance of the capacitor which depends upon soil dielectric constant and thus on volumetric content of soil moisture**[1]-[3]**. This frequency is measured and the moisture content of the soil is determined from it.

The FDR is the technique that has been introduced recently**[4]**. Previously TDR technique has been used for both cable testing purpose as well as for soil moisture determination but FDR has become the fastest and most accurate technique as compared to TDR technique. Frequency domain reflectometry (FDR) is rapidly gaining popularity in applications**[5]-[8]** above 200MHz. The basic differences between the FDR sensors introduced are related to the use of the capacitive sensor used in the probe of the sensor system design. Previously the capacitive sensor**[9]-[13]** was used as separate capacitor to which oscillating frequency signal was applied and subsequent changes in the output frequency of the capacitive sensor depends on the variation of capacitance of capacitive sensor and thus with the variation in soil dielectric constant or soil moisture.

The FDR sensor developed here uses the capacitor of probe sensor**[14]-[16]** in different way. The capacitor of the capacitive sensor is used as a part of LC oscillator whose oscillation frequency varies with change in capacitance of capacitor which in turns depends upon the variation in soil dielectric constant or soil moisture.

The sensor system is a system for measuring the soil moisture based on capacitance variation in the capacitive probe sensor, where in variation is the difference between varying or nominal value and the actual or capacitance value when there is no soil acting as dielectric medium. A calibration equation[17]-[18] is derived between the capacitance of he capacitive probe sensor and the moisture content of the soil and the frequency of the oscillator and the capacitance of the capacitive probe sensor. It includes LC oscillator, an impedance/spectrum analyzer, interface between the analyzer and computer and computer for the recording and analyzing the data.

The probe sensor[19]-[25] consists of two parallel plate capacitors which are penetrated into soil to determine the moisture content of the soil. The capacitance of the probe sensor depends on the moisture content of the soil. When the dry soil is present between the plates of the capacitor then the dielectric constant of the soil is 4 and when the water is present between the plates of the capacitor then the dielectric constant is 80. Since the capacitance of the capacitor depends on the dielectric constant of the medium between the plates of the capacitor thus the capacitance of the probe sensor increases with increase in the soil moisture content. The capacitance of the probe sensor forms the part of the LC tank circuit of the Colpitts oscillator thus the output frequency of the oscillator depends on the capacitance of the probe sensor and thus on the soil moisture content. The impedance/spectrum analyzer is used to determine the capacitance of the probe sensor and the output frequency of the oscillator. The data from the analyzer is fed into a computer through an interface between analyzer and the computer. The corresponding soil moisture content is determined using POGO soil moisture sensor. Thus a set of data is obtained consisting of capacitance and frequency for a corresponding moisture content. The data is analyzed through various statistical techniques and a prediction equation between the frequency and soil moisture content for the oscillator is determined which is fed into computer. The soil moisture content is determined from this prediction equation.

The two components of the FDR sensor system which are to be designed and implemented in hardware are:-

1. Capacitive probe sensor.
2. Colpitts oscillator for 50MHz frequency.

Both of these components are first designed through simulation for effective implementation in hardware. Thus there are two designs which are taken into consideration:-

1. Capacitive probe sensor design.
2. Colpitts oscillator design.

The FDR sensor system is implemented on hardware and experiments are done on soil samples prepared. The experiments are done in order to determine the calibration equation for the FDR sensor system which gives the relationship between the soil moisture and frequency of the oscillator. After the determination of the calibration equation the testing of the FDR sensor system can be done on soil samples prepared and the accuracy of the FDR sensor system can be determined after comparison with standard soil moisture sensor.

The experiments consist of preparation of soil samples, measurement of the capacitance and frequency of the FDR sensor system for the given soil moisture using the Agilent4396B impedance/spectrum analyzer, measurement of the soil moisture of the given samples using POGO soil moisture sensor and interfacing of the impedance/spectrum analyzer and computer for recording and analyzing the data. A sample of soil is prepared in a container. The soil is kept fine with less number of rocks, organic material and other materials in it. The soil moisture at different regions of the container is kept different in order to do experiments in these different regions. The Agilent4369B impedance/spectrum analyzer is made to operate in impedance mode. An RF**[26]-[30]** frequency sweep of 100kHz to 1.8GHz is applied across the standard capacitance for the calibration of the impedance/spectrum analyzer. The IF bandwidth is kept 10kHz. The capacitance of the connection cables connecting the capacitive probe sensor to impedance/spectrum analyzer is measured for the compensation from the total capacitance measured by the impedance/spectrum analyzer. The capacitive probe sensor is dipped into the soil at certain region of the container and capacitance of the capacitive sensor is measured and recorded on the computer. The soil moisture of that region is then measured by the POGO soil moisture sensor. The measurement of the capacitance is done in various regions of the container. The Agilent4369B impedance/spectrum analyzer is made to operate in spectrum mode. The capacitive sensor is connected to the Colpitts oscillator which is connected to the impedance/spectrum analyzer. The frequency of the oscillator is measured for the same regions of the container. The experiment is again done in the intervals of one hour on order to measure the different moisture of the same region at different times. Thus the soil moisture, capacitance and frequency of the oscillator is measured and recorded on the computer. This data is analyzed**[31]-[36]** to obtain the calibration equation of the FDR sensor system.

CHAPTER 2

BASIC DESIGN MODULE OF FDR SENSOR SYSTEM

2.1 SYSTEM ELEMENTS DETAILS:-

There are two ways through which the FDR sensor system is designed and implemented in hardware:-

2.1.1 FDR SENSOR SYSTEM USING FREQUENCY COUNTER:-

The sensor system consists of the following elements:-

1. A probe sensor consisting of a capacitive sensor having varying capacitance.
2. Electronic processing circuitry for processing of the signal sent by probe sensor.
3. Data computational algorithm unit.
4. Display unit.

1. BASIC DESIGN MODULE OF FDR:-

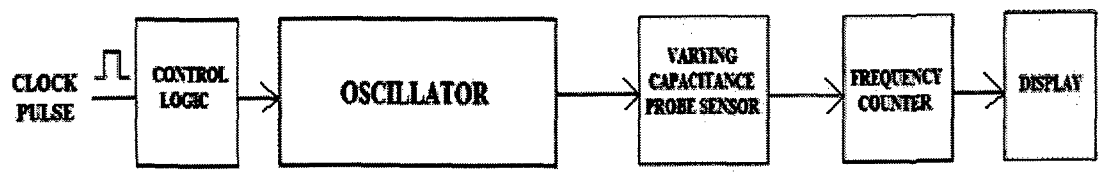

Fig.2.1 Basic block diagram of an FDR sensor system

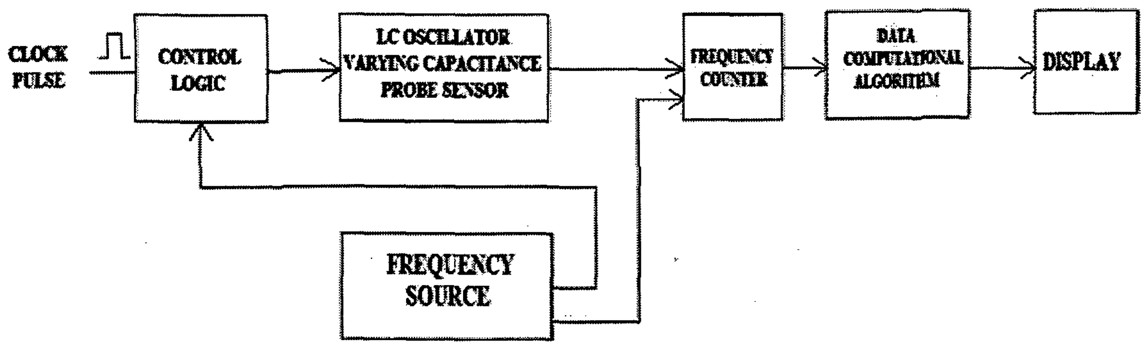

Fig.2.2 Block diagram of an FDR sensor

2. COMPONENTS:-

1. LC oscillator source (50 MHz).
2. Capacitive probe sensor.
3. Frequency source (Microcontroller) (16MHz).
4. Control logic (JK Flip Flop)
5. Frequency counter.
6. Three frequency dividers (by 16-divider, by 2-divider)
7. Three AND gates.
8. Data computational algorithm.
9. Display.

3. DETAILED WORKING OF FDR SENSOR SYSTEM:-

The sensor system is a system for measuring the soil moisture based on capacitance variation in the capacitive probe sensor, where in variation is the difference between varying or nominal value and the actual or capacitance value when there is no soil acting as dielectric medium. It includes LC oscillator, a circuit for capturing the output of LC oscillator, and computational unit for comparing the captured output to reference output and to evaluate the variation. Also the electronic circuit can detect directly the variation of capacitance without comparison with reference output.

LC oscillator used here is Colpitts oscillator producing an output of 50 MHz sinusoidal wave. In operation of system according to this embodiment the first step is providing a start pulse to control. The control logic then enables LC oscillator. At the same time, control logic also sends a high signal to AND gate, thereby enabling input of the 16 MHz (fref) reference signal to by 16-divider. The output of the divider is the input of the by 2-divider, the output of which is fed to AND gate. Sensor system is designed to allow to come to steady state before any measurement are made and such feature is provided by both dividers and AND gate. The output of by 2-divider is a square that stars low (binary zero), such that the first fref/16 cycles cause a zero to be input into AND gate. The one causes AND gate to output the pulses that it receives from by 8-divider (depending whether further delay is required for the output of oscillator to be stabilized to its steady state value). Thus the first fref/16 cycles is used to allow LC oscillator to reach steady state before its output is captured. The second fref/16 cycles are the measurement period, wherein a frequency counter captures the divided output of LC oscillator. In this design, the measurement period lasts 1 μsec. The control logic disables LC oscillator after the end of the second fref/16 cycles. Returning to the operation of LC oscillator the output thereof is fed to by 2-divider and to the AND gate. LC oscillator is designed such that if there is zero variation in capacitive sensor capacitor, then LC oscillator will output a 50 MHz pulse. If the capacitor has larger than actual capacitance, then the frequency of LC oscillator will be lower than 50 MHz. On the other hand, if the capacitance of capacitor is smaller than its actual value, then the frequency will be higher. The capacitor change is an inverse squared function of the frequency change.

Sensor system captures the output of LC oscillator by counting the pulses of its divided output. The LC oscillator ideally causes counter to store a value of fifty during the 1μsec measurement period. Thus, capacitive variation is measured by comparing the value stored in counter to the ideal one 50 reference output. Each least significant bit difference in the stored value represents a 0.78125% change in frequency of 50 MHz. The contacts of counter is sent to computation unit, which compares the stored value from fifty, and from that comparison, evaluates the capacitor variation. Different techniques to evaluate capacitor variation from different in stored output are possible. In one way, the difference in the stored output is used to calculate the frequency of LC oscillator. The computational unit then uses the frequency to find the capacitor variation in a look-up table. In another, computational unit inputs the oscillator frequency into mathematical algorithm that calculates the capacitor variation from frequency, the inductive value, the nominal value of capacitance of the capacitive sensor.

2.1.2 FDR SENSOR SYSTEM USING IMPEDANCE/SPECTRUM ANALYZER:-

The sensor system consists of the following elements:-

1. A probe sensor consisting of a capacitive sensor having varying capacitance**[4][6]**.
2. Electronic processing circuitry for processing of the signal sent by probe sensor.
3. Impedance/spectrum analyzer for the measurement and display of capacitance of the probe sensor and output frequency of the oscillator used and interfacing the analyzer to computer for the analysis of the data.

1. COMPONENTS:-

1. LC oscillator source (50 MHz).

2. Capacitive probe sensor.
3. Agilent 4369B impedance/spectrum analyzer.
4. Control logic (JK Flip Flop)
5. Interface between analyzer and computer.
6. Computer.

2. BASIC DESIGN MODULE OF FDR:-

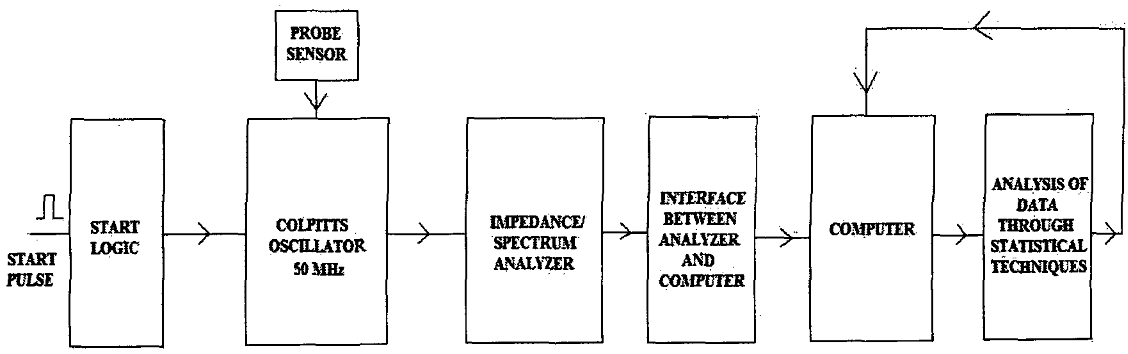

Fig.2.3 Block diagram of the electronic circuitry of FDR sensor system

3. COMPONENTS DESCRIPTION:-

1. LC oscillator source:-

For the generation of input signal pulse train an LC oscillator is used. The LC oscillator used in the sensor design circuitry is Colpitts linear oscillator is used.

A *Colpitts oscillator*, named after its inventor Edwin H. Colpitts, is one of a number of designs for electronic oscillator circuits using the combination of an inductance (L) with a capacitor (C) for frequency determination, thus also called LC oscillator. One of the key features of this type of oscillator is its simplicity (needs only a single inductor) and robustness.

The frequency is generally determined by the inductance and the two capacitors at the bottom of the drawing.

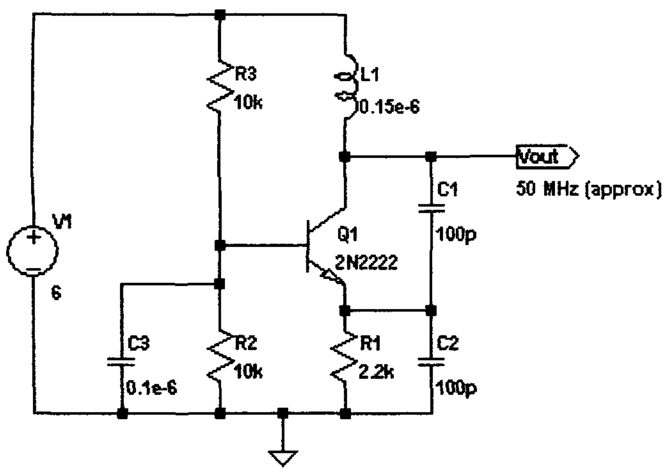

Fig.2.4 Practical common base Colpitts oscillator (with an oscillation frequency of ~50 MHz)

2. CONTROL LOGIC:-

A control logic is used to start and stop the LC oscillator to generate a signal for fixed interval of time. In order to implement a control logic a J-K flip-flop is used.

CHAPTER 3

AGILENT 4369B IMPEDANCE/SPECTRUM ANALYZER

3.1 AGILENT 4369B IMPEDANCE/SPECTRUM ANALYZER:-

The Agilent 4369B impedance/spectrum analyzer is an instrument which measures the impedance and spectrum of a device with a very high accuracy. The impedance/spectrum analyzer not only gives the measured value of impedance or spectrum but it also gives a resonance curve between the impedance or spectrum to be measured and the range or band of the frequencies applied across the device. A wide variety of analysis can be done on the impedance or spectrum measured with the impedance/spectrum analyzer. The impedance/spectrum analyzer can be interfaced with the computer for the recording and analyzing the data.

1. Key Features:-

1. High performance network, spectrum, impedance analyzers in a single box.
2. Built-in IBASIC.
3. GPIB port, digital I/O port.

2. Network Analysis:-

1. Frequency range: 100 kHz to 1.8 GHz.
2. 120 dB dynamic range @ 10 Hz IFBW.
3. +- 0.05 dB, +- 0.3 dynamic accuracy.

3. Spectrum Analysis:-

1. Frequency range: 2 Hz to 1.8 GHz.
2. -147 dB/Hz sensitivity @ 1 GHz.
3. Lower than +- 1 dB level accuracy.
4. Time-gated spectrum analysis option (4396B-1D6).

4. Impedance Analysis (Option 4396B-010):-

1. Frequency range: 100 kHz to 1.8 GHz.
2. Equivalent circuit analysis function.

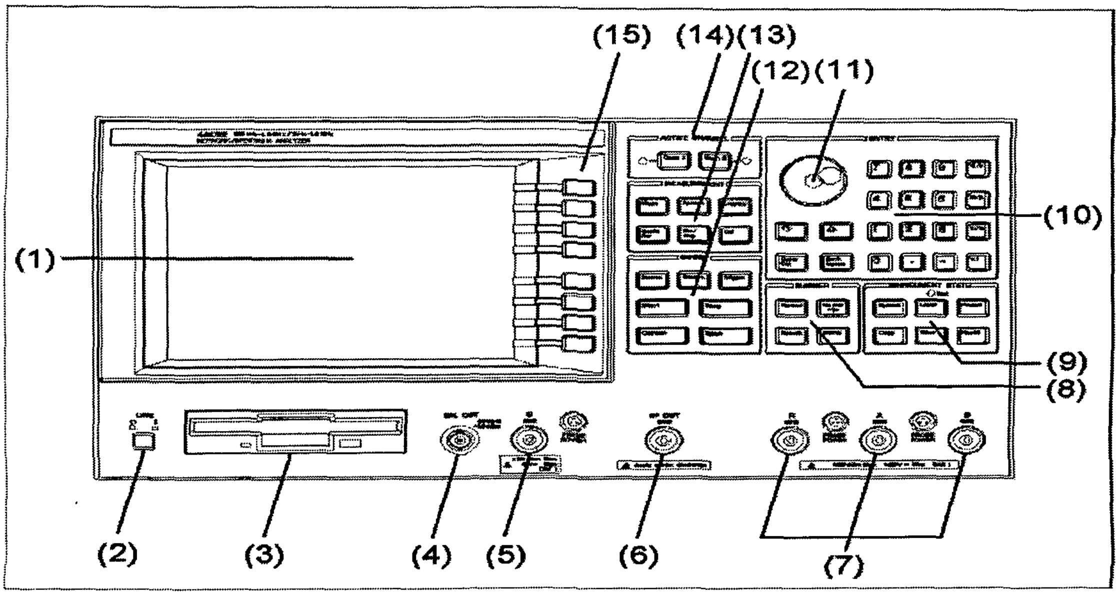

Fig.3.1 Agilent impedance/spectrum analyzer front view

1. LCD displays measured results, softkey menus, current settings, system messages, error messages, and Instrument BASIC programs.
2. LINE switch turns the analyzer ON and OFF.
3. 3.5 inch disk drive is used to store measurement results, instrument settings, display images, and Instrument BASIC programs.
4. CAL OUT (spectrum analyzer calibration output port) supplies a reference signal (20 MHz, -20 dbm) for reference level calibration.
5. S input (spectrum analyzer input) receives a signal for a spectrum measurement.
6. RF OUT (RF signal output port) supplies a source signal for network measurements.
7. R, A, and B inputs (RF signal inputs) mainly accept signals for network measurements, but can also be used as spectrum measurement inputs.
8. MARKER block contains keys related to the marker functions.
9. INSTRUMENT STATE block contains keys related to setting analyzer functions.
10. ENTRY block contains numerical keys, rotary knob, increment/decrement keys, edit keys, and unit-terminator keys.
11. Rotary knob changes displayed value by turning the knob.
12. SWEEP block contains keys related to the sweep functions.
13. MEASUREMENT block controls the measurement and display functions.
14. ACTIVE CHANNEL block selects the active channel as 1 or 2.
15. Softkeys used with hierarchical menus that are displayed by pressing hardkeys. Pressing a softkey activates the displayed function or accesses a lower level menu.

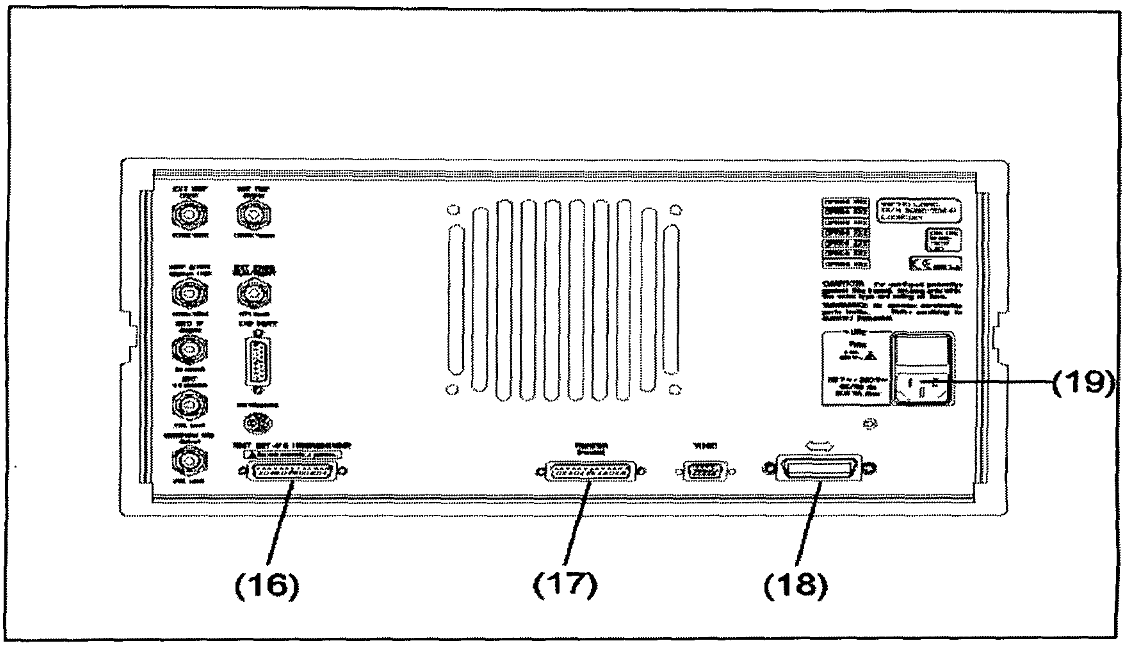

Fig.3.2 Agilent impedance/spectrum analyzer rear view

16. TEST SET-I/O INTERCONNECT connects the S-parameter test set to the analyzer.

17. Parallel interface connects the printer to the analyzer.

18. GPIB interface controls an GPIB instrument or can be controlled by an external controller.

19. Power cable receptacle connects the power cable. Fuse is held in the cover of the receptacle.

3.2 MEASUREMENT OF THE IMPEDANCE BY THE IMPEDANCE/SPECTRUM ANALYZER:-

The impedance of the device is measured by connecting the device to a test kit fixture. An impedance test kit 43961A is connected to the impedance/spectrum analyzer. The R and A output of the impedace test kit are connected to the 50Ω R and 50Ω A inputs of the impedance/spectrum analyzer. The RF OUT output of the impedance/spectrum analyzer is connected to the RF IN input of impedace test kit through an N-N cable. The RF out ouput of the impedance/spectrum analyzer applies a range or band of frequencies across the device. Three calibration standards short,open and 50Ω are used to calibrate the impedance test kit. A test kit fixture 16092A is connected to the impedance test kit. The test kit fixture is calibrated by using short and open standards. The device is then connected to the test kit fixture. The method used for the measurement of the impedance is RF I-V method.

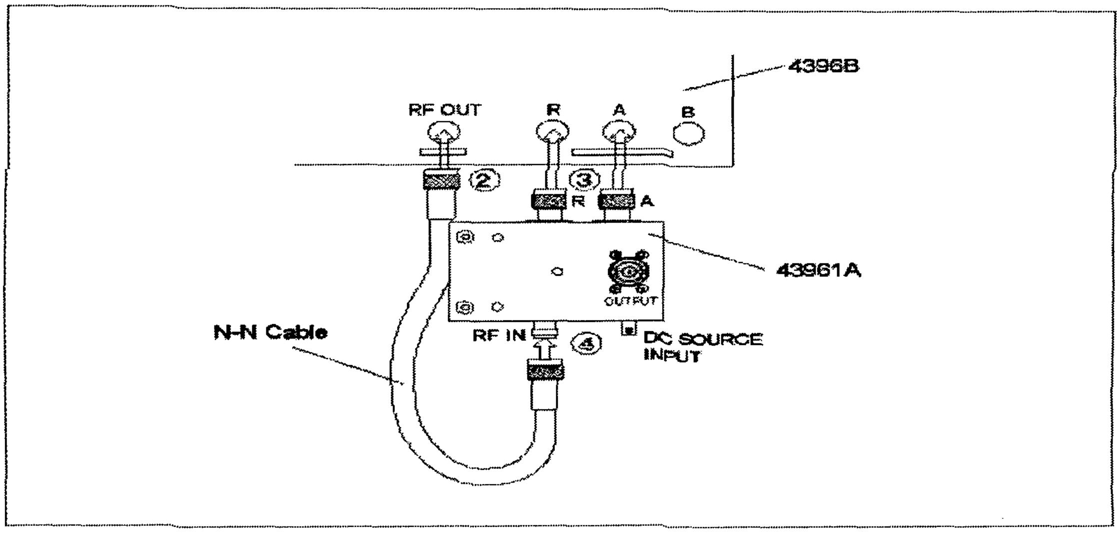

Fig.3.3 Impedance test kit

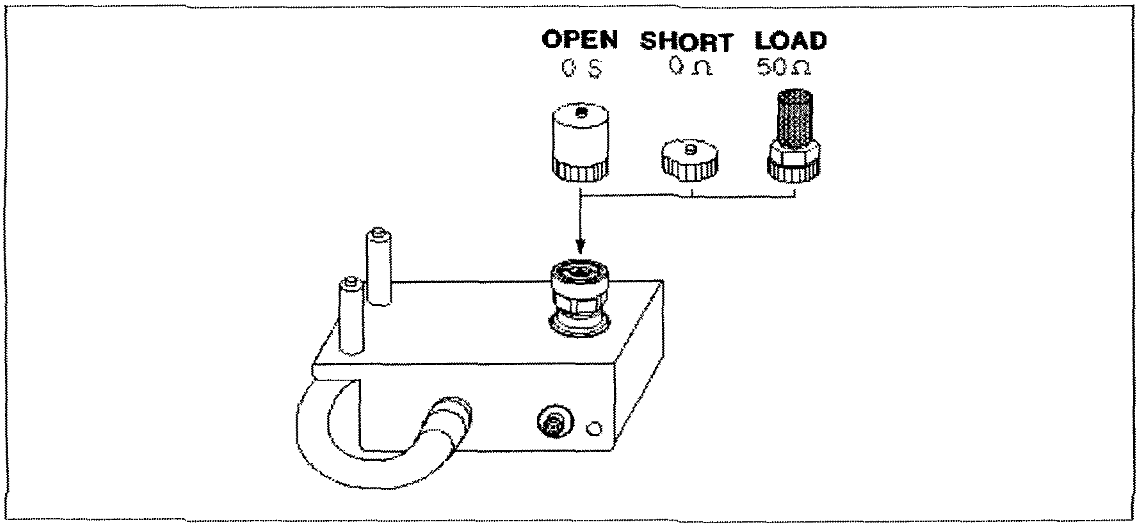

Fig.3.4 Calibration standards

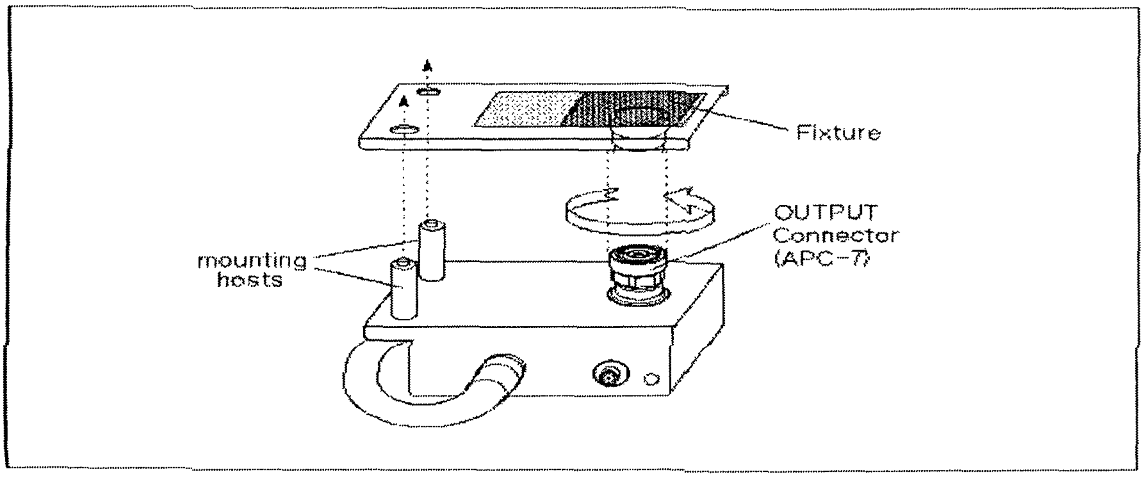

Fig.3.5 Test kit fixture

3.2.1 I-V Measurement Method:-

The 4396B, when combined with the 43961A, uses an I-V measurement method to measure the impedance of a DUT.

1. Basic concept of I-V method:-

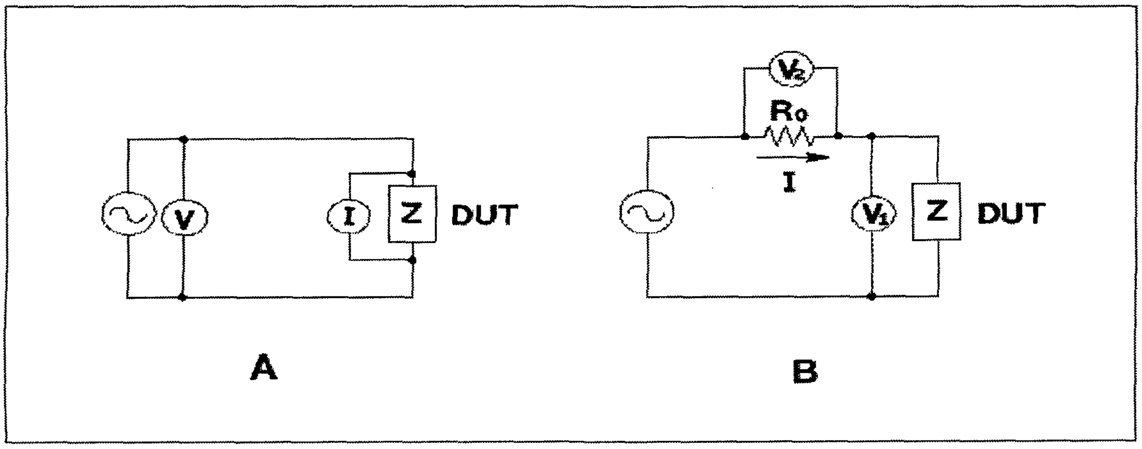

Fig.3.6 I-V Measurement Method

The unknown impedance, Z, can be calculated from the measured voltage and current using Ohm's law:

$$Z = V/I$$

The current, I, can be also obtained by the voltage level of the known resistance, R0.

$$Z = V1/I = V1 * R0/V2$$

The 4396B uses circuit B to determine the unknown impedance.

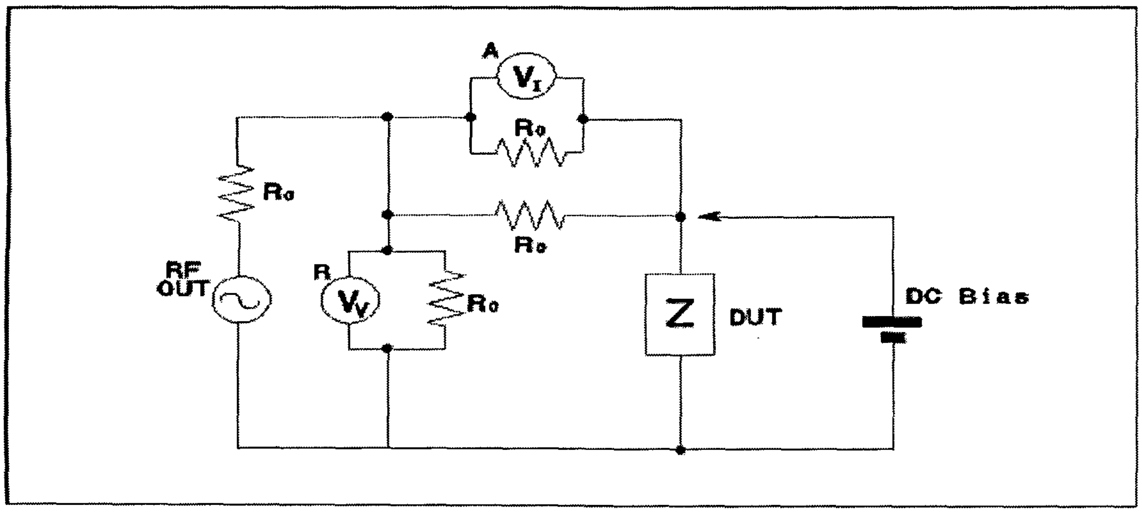

Fig.3.7 Impedance test kit block diagram

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2. Theory of RF I-V measurement method:-

The RF I-V method featuring Agilent's RF impedance analyzers and RF LCR meters is an advanced technique to measure impedance parameters in the high frequency range, beyond the frequency coverage of the auto-balancing bridge method. It provides better accuracy and a wider impedance range than the network analysis (reflection coefficient measurement) instruments can offer. This section discusses the brief operating theory of the RF I-V method using a simplified block diagram as shown in Figure 3.8.

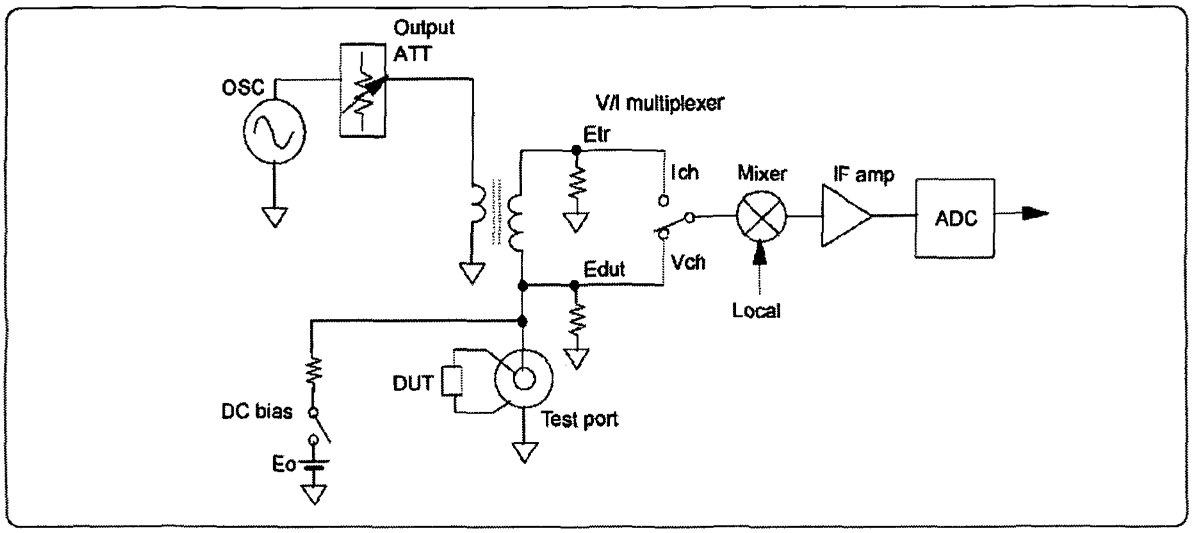


Fig.3.8 Simplified block diagram of RF I-V method

The signal source section generates an RF test signal applied to the unknown device and typically has a variable frequency range from 1 MHz to 3 GHz. Generally, a frequency synthesizer is used to meet frequency accuracy, resolution, and sweep function needs. The amplitude of signal source output is adjusted for the desired test level by the output attenuator.

The test head section is configured with a current detection transformer, V/I multiplexer, and test port. The measurement circuit is matched to the characteristic impedance of 50 Ω to ensure optimum accuracy at high frequencies. The test port also employs a precision coaxial connector of 50 Ω characteristic impedance. Since the test current flows through the transformer in series with the DUT connected to the test port, it can be measured from the voltage across the transformer's winding.

The V channel signal, E_{dut}, represents the voltage across the DUT and the I channel signal (E_{tr}) represents the current flowing through the DUT. Because the measurement circuit impedance is fixed at 50 Ω, all measurements are made in reference to 50 Ω without ranging operation.

The vector ratio detector section has similar circuit configurations as the auto-balancing bridge instruments. The V/I input multiplexer alternately selects the E_{dut} and E_{tr} signals so that the two vector voltages are measured with an identical vector ratio detector to avoid tracking errors. The measuring ratio of the two voltages derives the impedance of the unknown device as $Z_x = 50 \times (E_{dut}/E_{tr}.)$ To make the vector measurement easier, the mixer circuit down-converts the frequency of the E_{dut} and E_{tr} signals to an IF frequency suitable for the A-D converter's operating speed. In practice, double or triple IF conversion is used to obtain spurious-free IF signals. Each vector voltage is converted into digital data by the A-D converter and is digitally separated into 0° and 90° vector components.

3.3 Key measurement functions:-

1. OSC level:-

The oscillator output signal is output through the coaxial test port (coaxial connector) with a source impedance of 50 Ω. The oscillator output level can be controlled to change the test signal level applied to the DUT. Specified test signal level is obtained when the connector is terminated with a 50 Ω load (the signal level for open or short condition is calculated from that for 50 Ω.) When a DUT is connected to the measurement terminals, the current that flows through the DUT will cause a voltage drop at the 50 Ω source impedance (resistive.) The actual test signal level applied to the device can be calculated from the source impedance and the DUT's impedance as shown in figure. Those instruments equipped with a level monitor function can display the calculated test signal level and measurement results.

2. Test port:-

The test port of the RF I-V instrument usually employs a precision coaxial connector to ensure optimum accuracy throughout the high frequency range. The coaxial test port allows RF test fixtures to be attached and the instrument to be calibrated using traceable coaxial standard terminations. The test port is a two-terminal configuration and does not have a guard terminal separate from a ground terminal. Therefore, the guarding technique does not apply as well to the RF I-V measurements as compared to network analysis.

3. Calibration:-

Most of the RF vector measurement instruments, such as network analyzers, need to be calibrated each time a measurement is initiated or a frequency setting is changed. The RF I-V measurement instrument requires calibration as well. At higher frequencies, a change in the instrument's operating conditions, such as environmental temperature, humidity, frequency setting, etc., have a greater effect on measurement accuracy. This nature of RF vector measurement makes it difficult to sufficiently maintain the calibrated measurement performance over a long period of time. Thus, users have to periodically perform requisite calibration.

Calibration is executed in reference to three standard terminations: open, short, and load. All three must be performed. To improve the accuracy of low dissipation factor measurements (high Q factor), calibration with a low-loss capacitor can be performed. The theory of calibration and appropriate calibration methods are discussed in Section 4.

4. Compensation:-

Two kinds of compensation functions are provided: open/short compensation for eliminating the errors due to test fixture residuals, and electrical length compensation for minimizing the test port extension induced error. Practical compensation methods are discussed in Section 4.

5. Measurement range:-

The RF I-V measurement method, as well as network analysis, covers the full measurement range from low impedance to high impedance without ranging operation. All measurements are made at single broad range.

3.4 MEASUREMENT OF SPECTRUM BY IMPEDANCE/SPECTRUM ANALYZER:-

The spectrum of the device is measured by connecting the device to the 50Ω S input of the impedance/spectrum analyzer. The analyzer has four inputs; S, R, A, and B. In most spectrum measurements, the S input is used. The R, A, and B inputs can also be used for a spectrum measurement, but the dynamic range of these inputs is 20 dB worse than the S input and the attenuator is not variable. Therefore, to get the most accurate results, the S input should be used for spectrum measurements. The device is connected to the 50Ω S input through the BNC cable and N to BNC adapter. The impedance/spectrum analyzer is tested for the 20 MHz at 20 dBm source of the impedance/spectrum analyzer by connecting the BNC cable to the CAL OUT output of the impedance/spectrum analyzer.

The device is then connected to the 50Ω S input of the impedance/spectrum analyzer. A spectrum is obtained consisting of peaks of the frequency of the device with a gain of -20 dBm and harmonics of the frequency with lower gains.

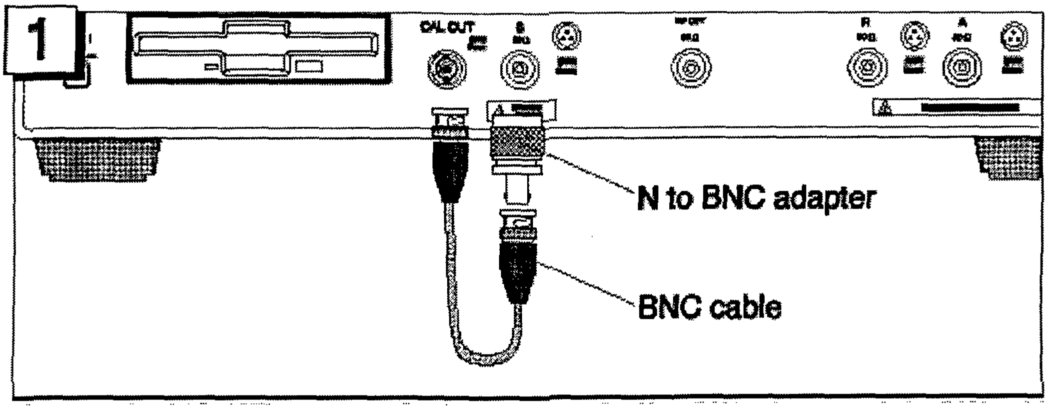


Fig.3.9 Connection of BNC cable and N to BNC cable to the CAL OUT output of impedance/spectrum analyzer

3.5 DETAILED WORKING OF FDR SENSOR SYSTEM:-

The sensor system is a system for measuring the soil moisture based on capacitance variation in the capacitive probe sensor, where in variation is the difference between varying or nominal value and the actual or capacitance value when there is no soil acting as dielectric medium. It includes LC oscillator, an impedance/spectrum analyzer, interface between the analyzer and computer and computer for the recording and analyzing the data. The probe sensor consists of two parallel plate capacitors which are penetrated into soil to determine the moisture content of the soil. The capacitance of the probe sensor depends on the moisture content of the soil. When the dry soil is present between the plates of the capacitor then the dielectric constant of the soil is 4 and when the water is present between the plates of the capacitor then the dielectric constant is 80. Since the capacitance of the capacitor depends on the dielectric constant of the medium between the plates of the capacitor thus the capacitance of the probe sensor increases with increase in the soil moisture content. The capacitance of the probe sensor forms the part of the LC tank circuit of the Colpitts oscillator thus the output frequency of the oscillator depends on the capacitance of the probe sensor and thus on the soil moisture content. The impedance/spectrum analyzer is used to determine the capacitance of the probe sensor and the output frequency of the oscillator. The data from the analyzer is fed into a computer through an interface between analyzer and the computer. The corresponding soil moisture content is determined using POGO soil moisture sensor. Thus a set of data is obtained consisting of capacitance and frequency for a corresponding moisture content. The data is analyzed through various statistical techniques and a prediction equation between the frequency and soil moisture content for the oscillator is determined which is fed into computer. The soil moisture content is determined from this prediction equation.

The second FDR sensor system design is chosen for the implementation of sensor system because of the following advantages:-

1. The second sensor system design is simpler as compared to first one. Thus it can be implemented easily on hardware.
2. It is easy to handle and maintenance cost is low because it consists of single Colpitts oscillator circuitry.
3. It is more accurate because overall accuracy of the sensor system is decreased due to Colpitts oscillator. The other components like impedance/spectrum analyzer and computer are highly accurate devices. While in other case the overall accuracy is decreased by the Colpitts oscillator, frequency counter, frequency dividers and AND gates.
4. Its manufacturing cost is low.

The two components of the FDR sensor system which are to be designed and implemented in hardware are:-

3. Capacitive probe sensor.
4. Colpitts oscillator for 50MHz frequency.

Both of these components are first designed through simulation for effective implementation in hardware. Thus there are two designs which are taken into consideration:-

3. Capacitive probe sensor design.
4. Colpitts oscillator design.

CHAPTER 4
CAPACITIVE PROBE SENSOR DESIGN

4.1 PROBE DESIGN RESULTS

The probe sensor is designed and simulated through the Integrated ELECTRO software. Three design configurations are taken into consideration.

1. Parallel plate capacitor.
2. Concentric cylindrical capacitor.
3. Rod electrode capacitor.

The variation of capacitance, electric field in the region between electrodes, fringing electric field in the region outside and near to the electrodes, resolution, accuracy, compaction of the soil inside the electrodes and compact probe design with variation in the shape and size of the electrodes are analyzed and an optimum design of the probe sensor is obtained from the analysis[3][4].

4.2 PARALLEL PLATE CAPACITOR:-

A Parallel plate capacitor is designed and simulated in the Integrated Electro software. The dimensions of the capacitor are:-

1. Diameter of electrode – 4 inch.
2. Thickness of the electrode – 0.5 inch.
3. Gap between the electrodes – 0.6 inch.
4. Diameter of the arc of the edge of the electrode – 0.5 inch.

The following parameters are calculated and analyzed for the parallel plate capacitor:-

1. VOLTAGE:-

The two electrodes of the capacitor are given -30V and 30V and the variation of the potential in the region around the electrodes is measured. The potential is maximum at the electrode and decreases with distance away from the electrode.

2. ELECTRIC FIELD:-

The electric field in two regions has been taken into consideration.

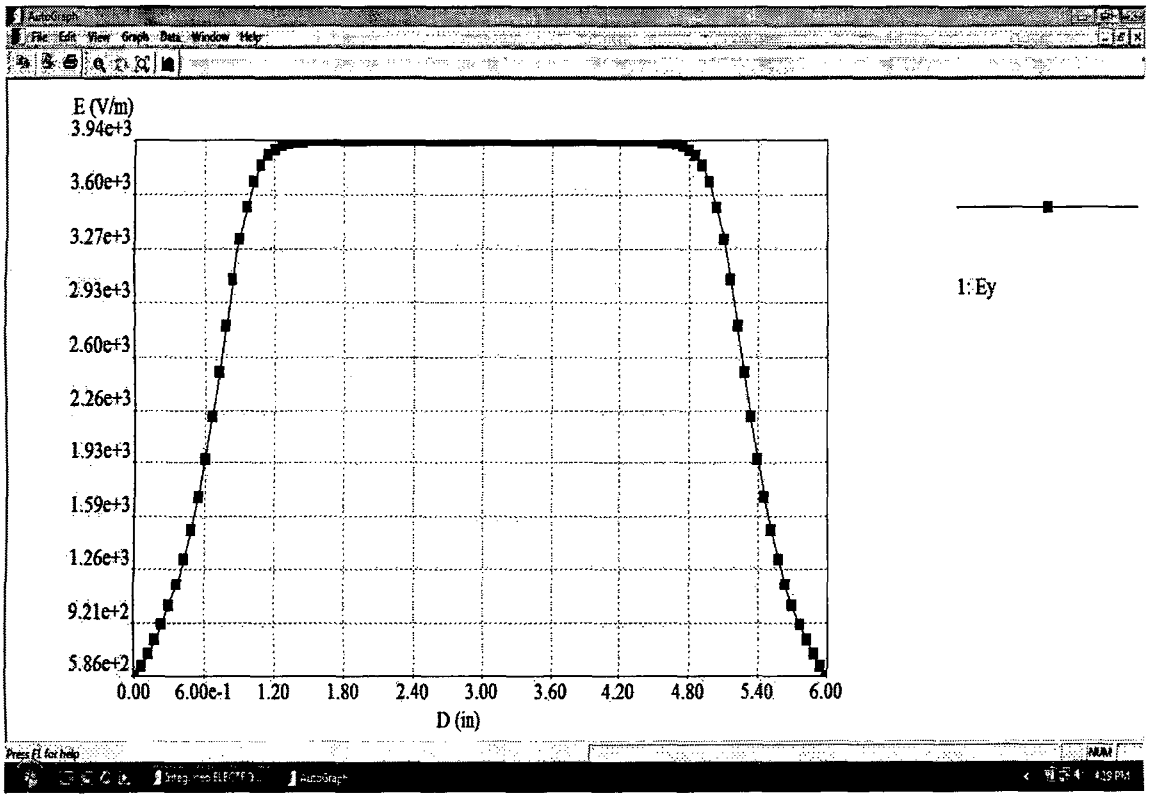


Fig.4.1 Electric field vs distance

1. ELECTRIC FIELD IN THE REGION BETWEEN ELECTRODES:-

The electric field in the region between the electrodes is stable, constant and very high 3.94 kV/m. Thus a very high, stable and constant electric field in the region between the electrodes increases the accuracy and sensitivity of the capacitive sensor. Because of the high and constant electric field in the region between the electrodes the electric field due to enviromental noise[5][6] will disorientate the dipoles less and thus increasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will be changed to the original orientation of the dipoles in the direction of the electric field and thus increasing the sensitivity of the capacitive sensor.

2. ELECTRIC FIELD IN THE REGION OUTSIDE AND NEAR TO THE EDGE OF THE ELECTRODES:-

The electric field outside and near to edge of the electrodes is the fringing electric field. This fringing electric field acts as enviromental noise[7][8] interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the readings.

The fringing field varies in the range of 3.94 kV/m to 0.586 kV/m when the distance is varied in x-axis between 1.20 inch to 0 inch.

3. CAPACITANCE:-

The charge accumulated in each plate of the capacitor is 535.7 pC when the dielectric medium is air. The charge accumulated in the plates changes from 535.7 pC to 890 pC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

4. RESOLUTION:-

The minimum charge accumulated on each plate is 535.7 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 8.69 pF. Thus the resolution of the capacitor for the dielectric medium of air is 8.69 pF.

5. SENSITIVITY:-

The sensitivity of the parallel plate capacitor is given by the equation

$$dC/d\varepsilon = \varepsilon_0 A/d$$

ε_0 = permittivity of the air

A = area of the each plate

d = gap between the plates

The sensitivity of the capacitor is 4.464 pF.

4.3 CONCENTRIC CYLINDRICAL CAPACITOR:-

A concentric cylindrical capacitor is designed and simulated in the Integrated Electro software. The dimensions of the capacitor are:-

1. Inner diameter of outer electrode – 2 inch.
2. Outer diameter of inner electrode – 0.8 inch.
3. Thickness of the each electrode – 0.2 inch.
4. Gap between the electrodes – 0.6 inch.
5. Length of each electrode – 2 inch.

The following parameters are calculated and analyzed for the parallel plate capacitor:-

1. VOLTAGE:-

The two electrodes of the capacitor are given -30V and 30V and the variation of the potential in the region around the electrodes is measured. The potential is maximum at the electrode and decreases with distance away from the electrode.

2. ELECTRIC FIELD:-

The electric field in two regions has been taken into consideration.

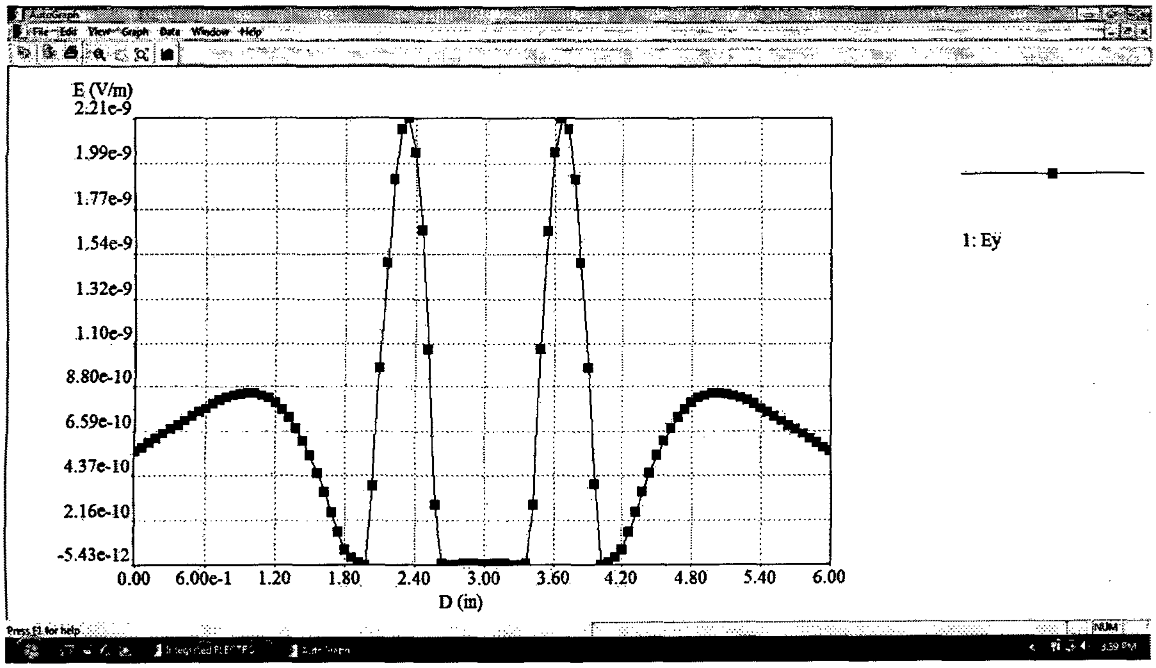


Fig.4.2 Electric field vs distance

1. ELECTRIC FIELD IN THE REGION BETWEEN ELECTRODES:-

The electric field in the region between the electrodes is not stable and constant. The electric field is very small. There are two peaks at which the electric field is 2.21 nV/m. The electric field between the points 2.6 and 3.4 is constant and small equal to -5.43 pV/m. Thus a very low, and varying electric field in the region between the electrodes decreases the accuracy and sensitivity of the capacitive sensor. Because of the low and varying electric field in the region between the electrodes the electric field due to enviromental noise will disorientate the dipoles more and thus decreasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will not be changed to the original orientation of the dipoles in the direction of the electric field and thus decreasing the sensitivity of the capacitive sensor.

2. ELECTRIC FIELD IN THE REGION OUTSIDE AND NEAR TO THE EDGE OF THE ELECTRODES:-

The electric field outside and near to the edge of the electrodes is the fringing electric field. This fringing electric field acts as enviromental noise interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the readings.

The fringing field increases in the range of -5.43 pV/m to 880 pV/m when the distance is varied in x-axis between 2.1 inch to 0.9 inch and then decreases in the range of 880 pV/m to 5.48 pV/m.

3. CAPACITANCE:-

The charge accumulated in positive plate of the capacitor is 502.5 pC and in the negative plate is -416.06 pC when the dielectric medium is air. The charge accumulated in the positive plate changes from 502.5 pC to 1.05 nC and in the negative plate changes from -416.06 pC to -976.04 pC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

4. RESOLUTION:-

The minimum charge accumulated on each plate is 502.5 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 8.37 pF. Thus the resolution of the capacitor for the dielectric medium of air is 8.37 pF.

5. SENSITIVITY:-

The sensitivity of the concentric cylinder capacitor is given by the equation

$$dC/d\varepsilon = 2\pi\varepsilon_0 l/\log(R1/R2)$$

ε_0 = permittivity of the air

l = length of the each plate

R1 = inner diameter of outer cylinder

R2 = outer diameter of inner cylinder

The sensitivity of the capacitor is 6.054 pF.

4.4 ROD ELECTRODE CAPACITOR:-

A Rod electrode capacitor is designed and simulated in the Integrated ELECTRO software. A single rod of the capacitor is designed in the Integrated ELECTRO software and results are obtained for it. These results are compared with results obtained for single parallel plate and results are obtained for two rod capacitor by analogy between two results. The dimensions of the capacitor are:-

1. Diameter of the electrode – 0.5 inch.
2. Length of the electrode – 2.5 inch.
3. Length of the cone – 0.5 inch.

The following parameters are calculated and analyzed for the single rod of the rod electrode capacitor and single plate of the parallel plate capacitor:-

1. VOLTAGE:-

The electrodes of the rod electrode capacitor and parallel plate capacitor are given 30V and the variation of the potential in the region around the electrodes is measured. The potential is maximum at the electrode and decreases with distance away from the electrode.

2. ELECTRIC FIELD:-

The electric field in the region along the length of the single rod electrode is less stable and constant as compared to the single plate electrode. The electric field for single rod electrode is low as compared to the single plate electrode. the electric field for the single rod electrode decreases from -1.14 kV/m to -1 kV/m between the points 3.15 inch and 4.05 inch and then increases to -1.09 kV/m between the points 4.05 inch and 4.95 inch. The electric field for single plate electrode decreases from -4.64 kV/m to -3.09 kV/m between the points 1.05 inch and 4.95 inch and then increases to -4.64 kV/m. Because the electric field for single rod electrode is less stable, constant and low as compared to the electric field for single plate electrode, the electric field for rod electrode capacitor will be less stable,constant and low as compared to the parallel plate capacitor. Thus a low, and varying electric field in the region between the electrodes decreases the accuracy and sensitivity of the capacitive sensor.

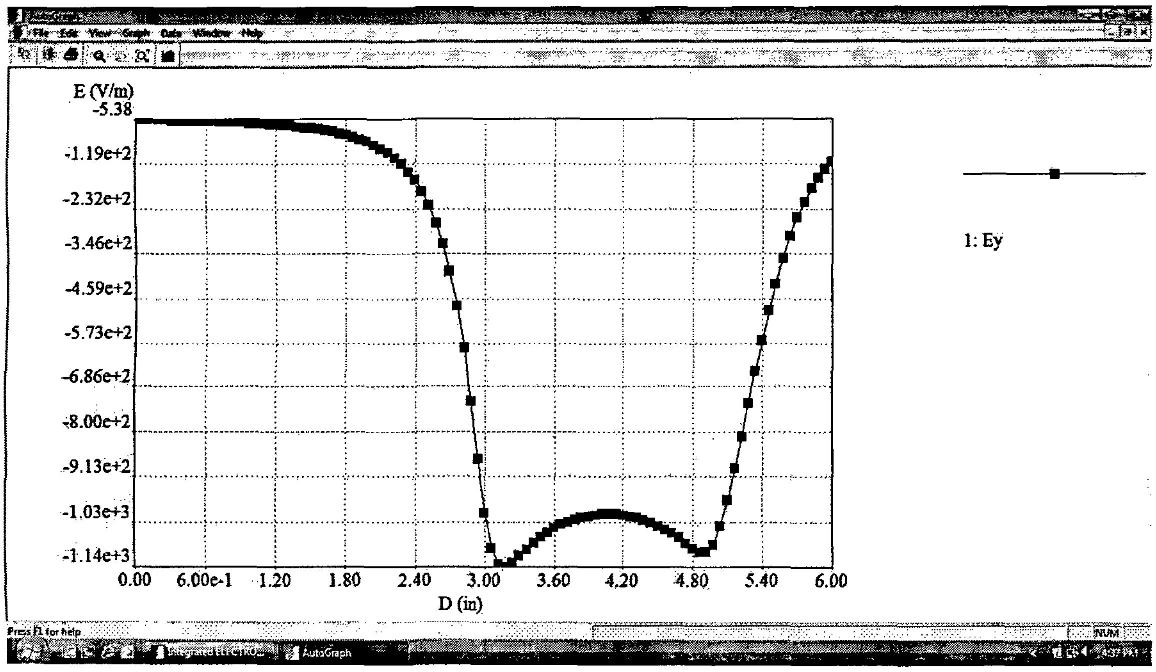


Fig.4.3 Electric field vs distance

Because of the low and varying electric field in the region between the electrodes the electric field due to enviromental noise will disorientate the dipoles more and thus decreasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will not be changed to the original orientation of the dipoles in the direction of the electric field and thus decreasing the sensitivity of the capacitive sensor.

3. ELECTRIC FIELD IN THE REGION OUTSIDE AND NEAR TO THE EDGE OF THE ELECTRODES:-

The electric field outside and near to the electrodes is the fringing electric field. This fringing electric field acts as enviromental noise interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the readings.

The fringing field varies in the range of -1.14 kV/m to -5.38 V/m when the distance is varied in x-axis between 3.15 inch to 0 inch on one side of the rod and -1.09 kV/m to -5.38 V/m when distance is varied in x-axis between 4.95 inch and 8 inch on other side of rod.

4. CAPACITANCE:-

The charge accumulated in each plate of the capacitor is 49.32 pC when the dielectric medium is air.

5. RESOLUTION:-

The minimum charge accumulated on single rod electrode is 49.32 pC and on the single plate electrode is 13.70 pC when the dielectric medium is air at the voltage of 30 V. The charge accumulate on each plate of of parallel plate capacitor at a voltage difference of 60V is 535.7 pC and the capacitance is 8.69 pF. The capacitance of the rod electrode capacitor is obtained as 32.14 pF. Thus the resolution of the capacitor for the dielectric medium of air is 32.12 pF.

4.5 EFFECTS OF VARYING DIMENSIONS OF CAPACITOR ON PARAMETERS:-

The dimensions of the three configurations of the capacitor are varied and the changes in the parameters are measured.

1. PARALLEL PLATE CAPACITOR:-

1. EFFECT OF THE VARIATION OF DIAMETER:-

The diameter of the parallel plate capacitor is varied and its effect on the parameters is measured.

1. ELECTRIC FIELD:-

The electric field in two regions is taken into consideration.

1. ELECTRIC FIELD IN THE REGION BETWEEN THE ELECTRODES:-

The diameter of the capacitor is increased from 4 inch to 5 inch and changes in the electric field are measured. The electric field is more stable and constant upto points 0.8 inch and 5.2 inch on both sides of the electrodes. The intensity of the electric field is same.

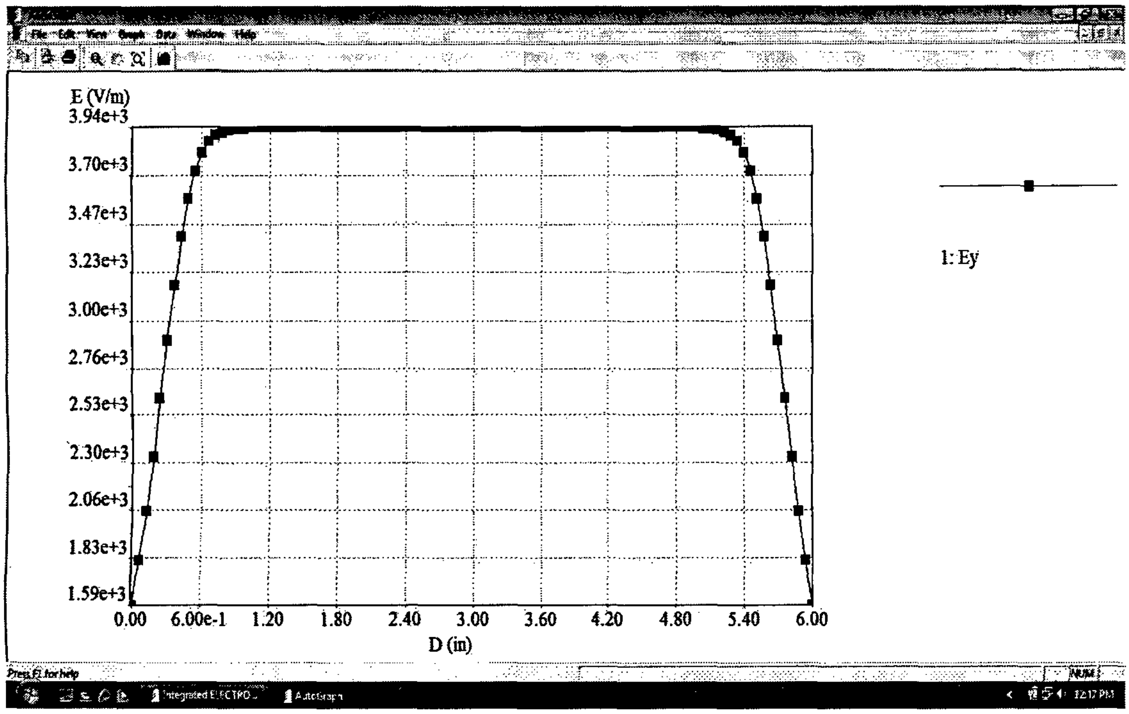


Fig.4.4 Electric field vs distance

2. ELECTRIC FIELD OUTSIDE AND NEAR TO THE EDGE OF ELECTRODES:-

The rate of the change of the fringing electric field is 2.94 kV/m inch. The rate of the change of the fringing electric field at the original length is 2.80 kV/m inch. Thus the fringing electric field decreases rapidly on increasing the length. Thus the fringing electric field has less effect on the components, connection cables and wires.

2. CAPACITANCE:-

The charge accumulated in positive plate of the capacitor is 633 pC and in the negative plate is -633 pC when the dielectric medium is air. The charge accumulated in the positive plate changes from 633 pC to 1.02 nC and in the negative plate changes from -633 pC to -1.02 nC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

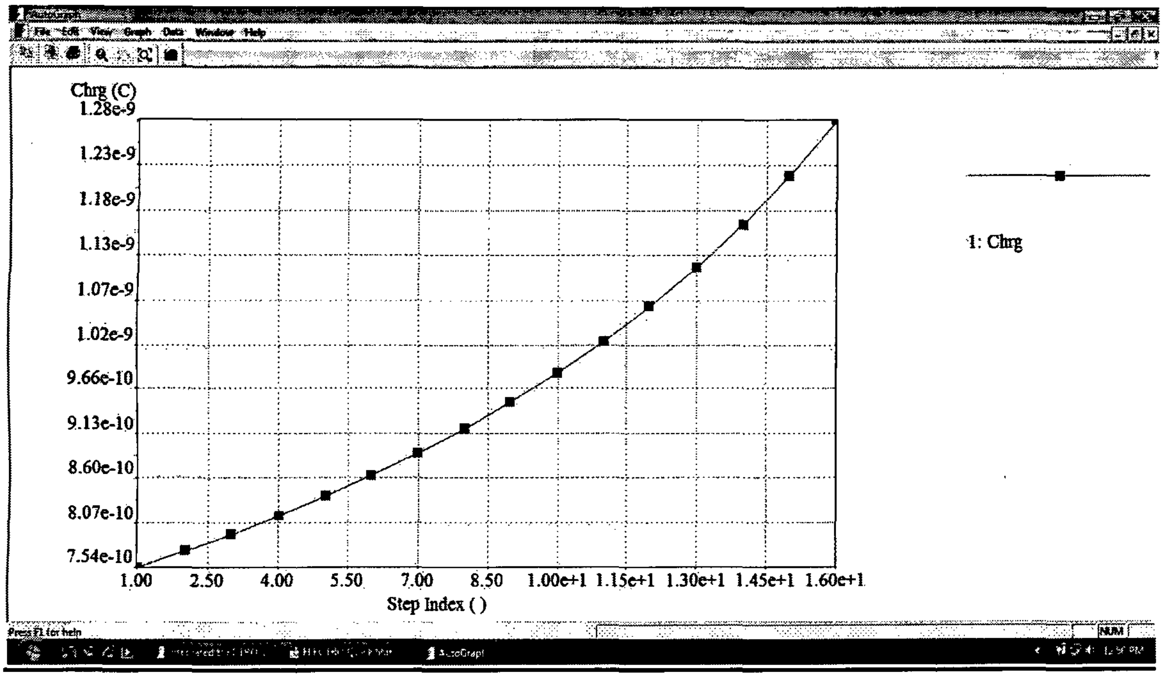


Fig.4.5 Capacitance vs gap

3. RESOLUTION:-

The minimum charge accumulated on each plate is 633 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 10.55 pF. Thus the resolution of the capacitor for the dielectric medium of air is 10.55 pF. Thus the resolution decreases from 8.37 pF to 10.55 pF on increasing the length.

4. SENSITITVITY:-

The sensitivity of the parallel plate capacitor is given by the equation

$$dC/d\varepsilon = \varepsilon_0 A/d$$

ε_0 = permittivity of the air

A = area of the each plate

d = gap between the plates

The sensitivity of the capacitor is 7.352 pF.

Thus the sensitivity decreases on increasing the length from 4.464 pF to 7.352 pF.

2. EFFECT OF THE VARIATION OF THICKNESS:-

The thickness of the parallel plate capacitor is varied and its effect on the parameters is measured.

1. ELECTRIC FIELD:-

The electric field in two regions is taken into consideration.

1. ELECTRIC FIELD IN THE REGION BETWEEN THE ELECTRODES:-

The thickness of the capacitor is increased from 0.5 inch to 1 inch and changes in the electric field are measured. The electric field is less stable and constant upto points 1.2 inch and 4.8 inch on both sides of the electrodes. The intensity of the electric field is same.

2. ELECTRIC FIELD OUTSIDE AND NEAR TO THE EDGE OF ELECTRODES:-

The rate of the change of the fringing electric field is 2.52 kV/m inch. The rate of the change of the fringing electric field at the original length is 2.80 kV/m inch. Thus the fringing electric field decreases slowly on increasing the thickness. Thus the fringing electric field has more effect on the components, connection cables and wires.

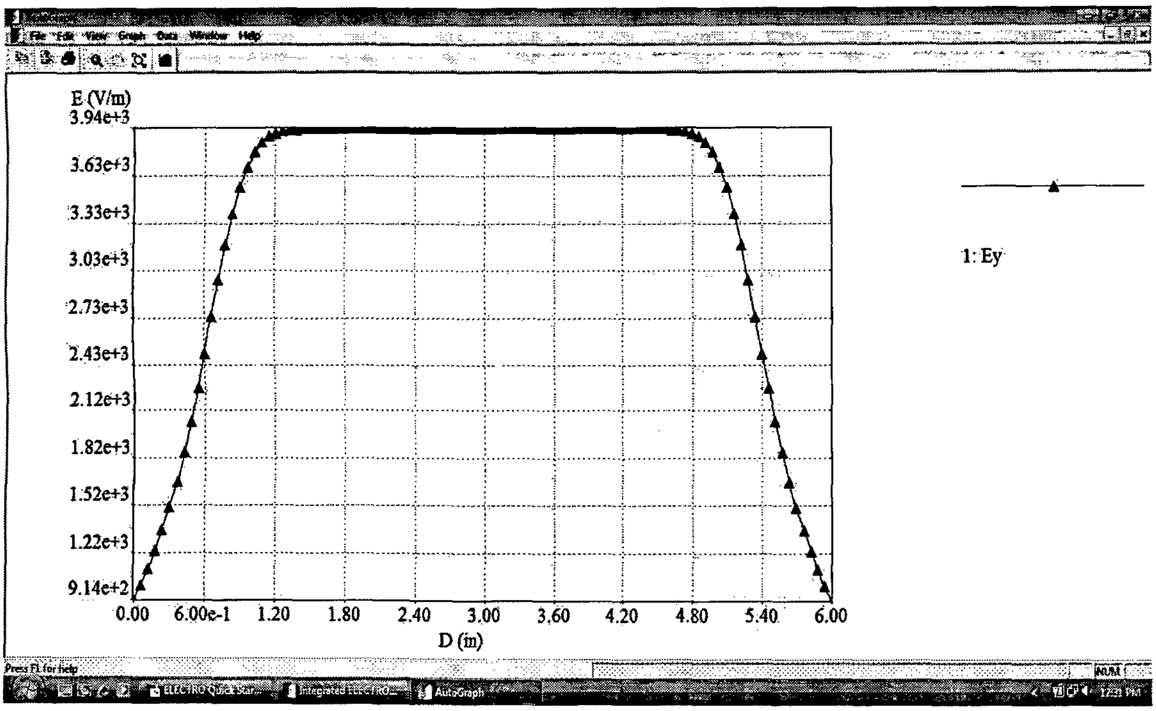


Fig.4.6 Electric field vs distance

3. CAPACITANCE:-

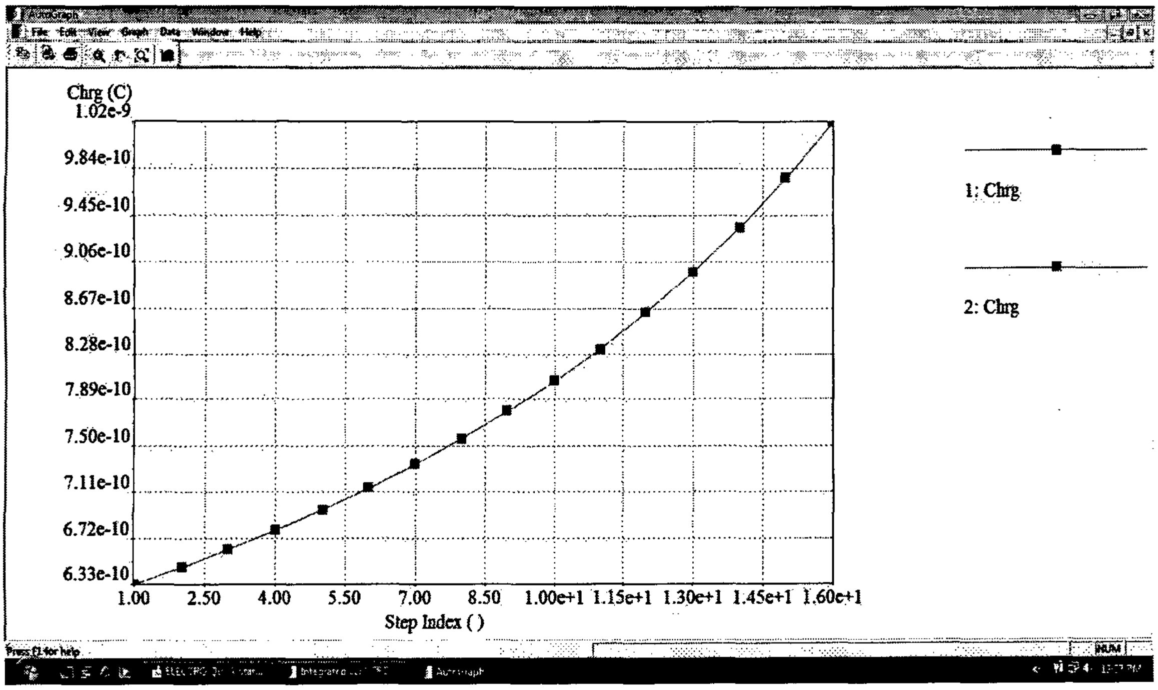


Fig.4.7 Electric field vs distance

The charge accumulated in positive plate of the capacitor is 633 pC and in the negative pla9te is -633 pC when the dielectric medium is air. The charge accumulated in the positive plate changes from 633 pC to 1.02 nC and in the negative plate changes from -633 pC to -1.02 nC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

4. RESOLUTION:-

The minimum charge accumulated on each plate is 633 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 10.55 pF. Thus the resolution of the capacitor for the dielectric medium of air is 10.55 pF. Thus the resolution decreases from 8.37 pF to 10.55 pF on increasing the length.

5. SENSITITVITY:-

The sensitivity of the parallel plate capacitor is given by the equation

$$dC/d\varepsilon = \varepsilon_0 A/d$$

ε_0 = permittivity of the air

A = area of the each plate

d = gap between the plates

The sensitivity of the capacitor is 4.464 pF.

Thus the sensitivity remains same on increasing the thickness.

2. CONCENTRIC CYLINDRICAL CAPACITOR:-

1. EFFECT OF THE VARIATION OF LENGTH:-

The length of the concentric cylindrical capacitor is varied and its effect on the parameters is measured.

1. ELECTRIC FIELD:-

The electric field in two regions is taken into consideration.

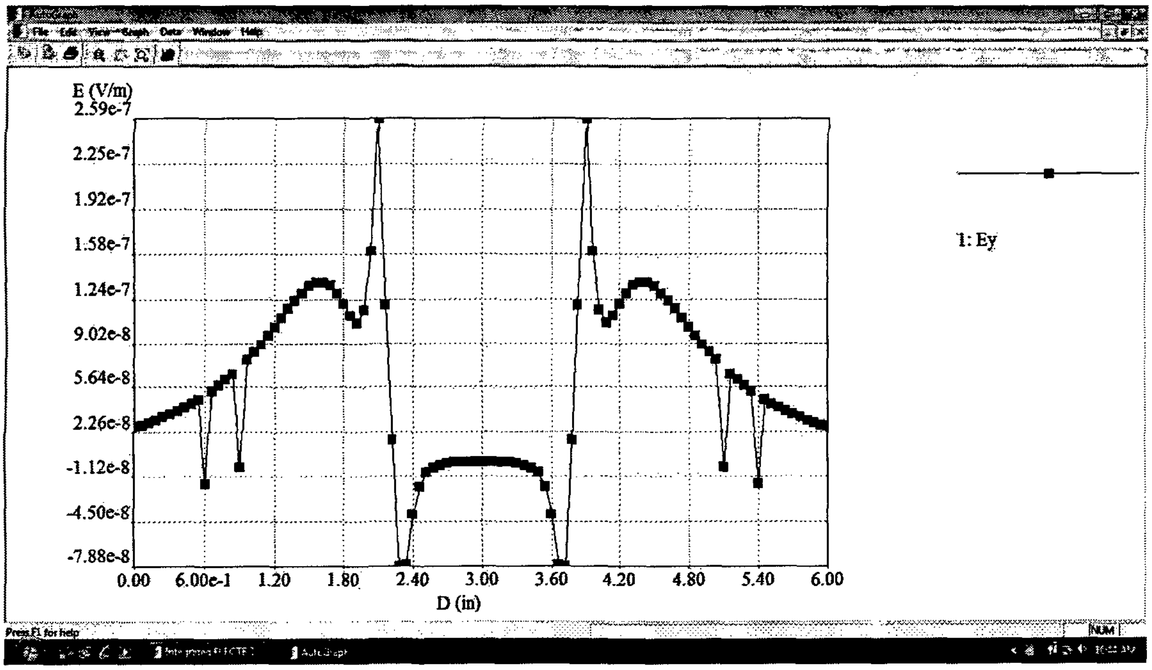


Fig.4.8 Electric field vs distance

1. ELECTRIC FIELD IN THE REGION BETWEEN THE ELECTRODES:-

The length of the capacitor is increased from 2 inch to 2.4 inch and changes in the electric field are measured. The electric field in the region between the electrodes is not stable and constant. The electric field is very small. The electric field at the two peaks increases from 221.9 pV/m to 259 nV/m. The electric field between the points 2.4 and 3.6 is constant and small increasing from -5.43 pV/m to 5.7 nV/m.

2. ELECTRIC FIELD OUTSIDE AND NEAR TO THE EDGE OF ELECTRODES:-

The fringing field increases in the range of 22.6 nV/m to 141 nV/m higher than the range for original length when the distance is varied in x-axis between 0 inch and 1.6 inch and 4.4 inch and 6 inch except at the points 0.6 inch, 0.9 inch, 5.1 inch and 5.4 inch where four peaks are obtained. The fringing electric fields at these points are -2.75 nV/m and 19.65 nV/m. The fringing electric field decreases in the range of 141 nV/m to 107 nV/m between 1.6 inch and 1.95 inch and 4.4 inch and 4.75 inch.

Thus the higher fringing electric field has more effect on the components, connection cables and wires.

2. CAPACITANCE:-

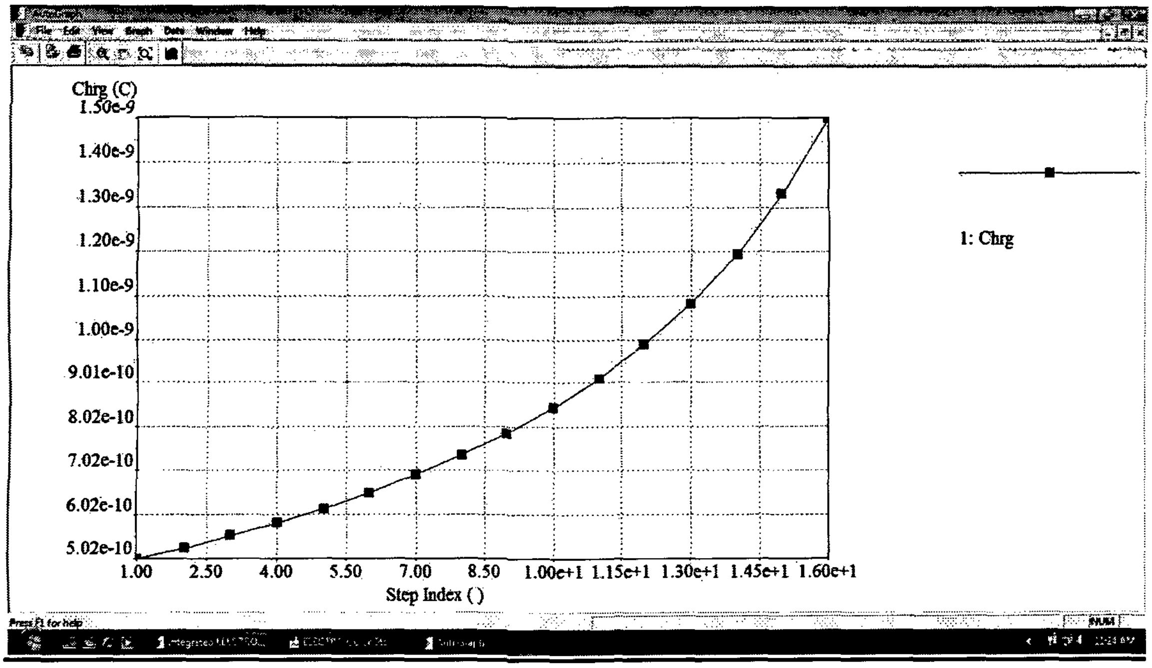


Fig.4.9 Capacitance vs gap

The charge accumulated in positive plate of the capacitor decreases from 502.05 pC to 502 pC and in the negative plate decreases from -416.06 to- 416 pC when the dielectric medium is air. The charge accumulated in the positive plate changes from 502 pC to 1.5 nC lower than the change in original length and in the negative plate changes from -416 pC to -1.42 nC lower than the change in the original length when the gap between plates is decreased from 0.6 inch to 0.3 inch.

3. RESOLUTION:-

The minimum charge accumulated on each plate is 502 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 8.37 pF. Thus the resolution of the capacitor for the dielectric medium of air is 8.37 pF. Thus the resolution remains same on increasing the length.

4. SENSITITVITY:-

The sensitivity of the concentric cylinder capacitor is given by the equation

$$dC/d\varepsilon = 2\pi\varepsilon_0 l/\log(R1/R2)$$

ε_0 = permittivity of the air

l = length of the each plate

R1 = inner diameter of outer cylinder

R2 = outer diameter of inner cylinder

The sensitivity of the capacitor increases from 6.054 pF to 2.444 pF.

3. EFFECT OF THE VARIATION OF THICKNESS:-

The thickness of the concentric cylidrical capacitor is varied and its effect on the parameters is measured.

1. ELECTRIC FIELD:-

The electric field in two regions is taken into consideration.

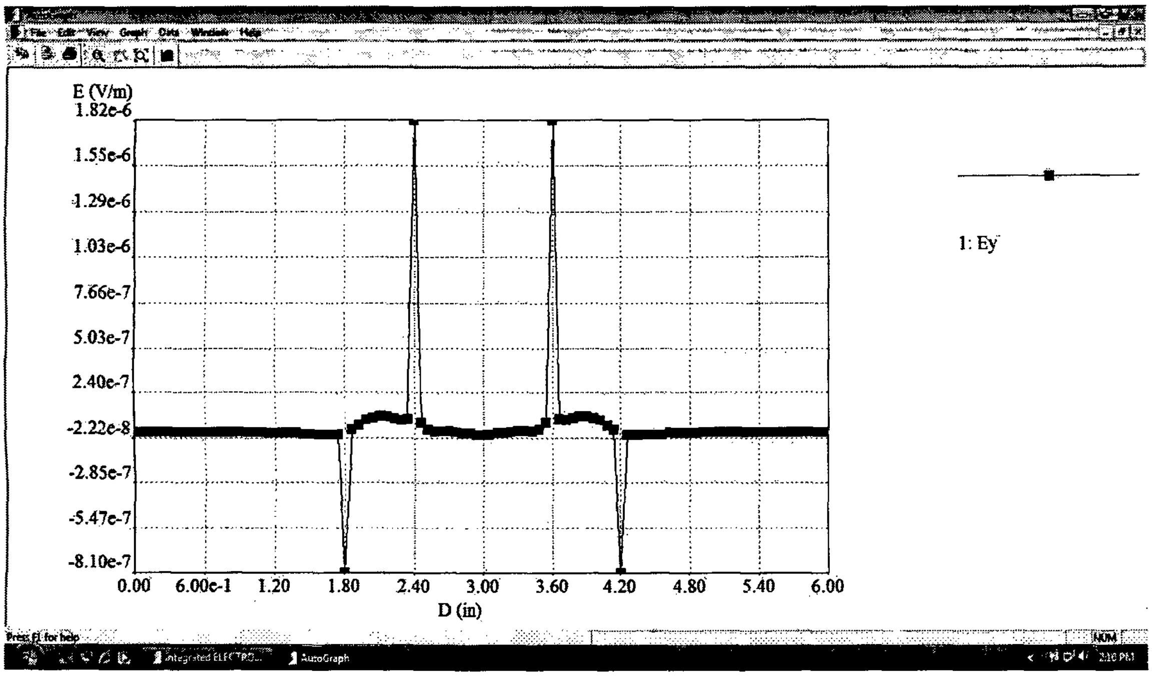


Fig.4.10 Electric field vs distance

1. ELECTRIC FIELD IN THE REGION BETWEEN THE ELECTRODES:-

The thickness of the capacitor is increased from 0.2 inch to 0.4 inch and changes in the electric field are measured. The electric field in the region between the electrodes is more stable and constant. The electric field is very small. The electric field at the two peaks increases from 221.9 pV/m to 1820 nV/m. The electric field between the points 2.4 and 3.6 is constant and small increasing from -5.43 pV/m to -22.2 nV/m.

2. ELECTRIC FIELD OUTSIDE AND NEAR TO THE EDGE OF ELECTRODES:-

The fringing field remains constant equal to -22.2 nV/m lower than the range for original length when the distance is varied in x-axis between 0 inch and 1.8 inch and 4.2 inch and 6 inch except at the points 1.8 inch and 4.2 inch where two peaks are obtained. The fringing electric field at these peaks is -81 nV/m. The fringing electric field increases from 32.8 nV/m to 109 nV/m lower than the range for original length when the distance is varied between 1.8 inch and 2.1 inch and then remains almost constant between 2.1 inch and 2.4 inch.

Thus the lower fringing electric field has less effect on the components, connection cables and wires.

2. CAPACITANCE:-

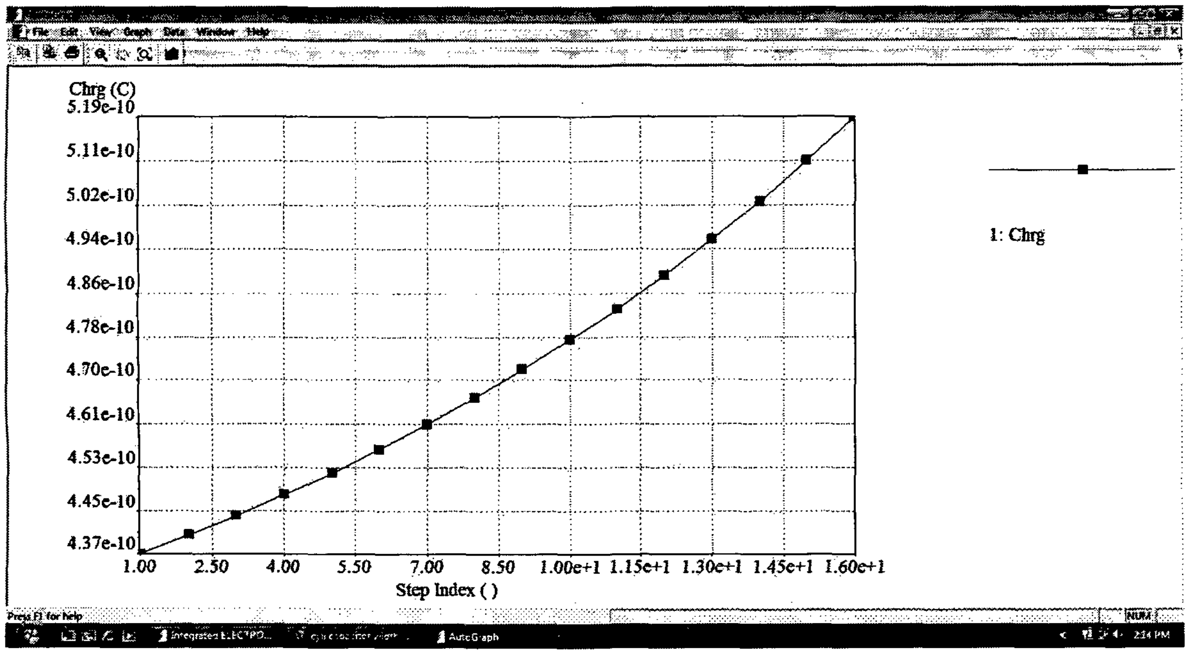


Fig.4.11 Capacitance vs gap

The charge accumulated in positive plate of the capacitor is 437 pC and in the negative plate is -320 pC when the dielectric medium is air. The charge accumulated in the positive plate changes from 437 pC to 519 pC and in the negative plate changes from -320 pC to -413 pC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

3. RESOLUTION:-

The minimum charge accumulated on each plate is 437 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is

7.28 pF. Thus the resolution of the capacitor for the dielectric medium of air is 7.28 pF. Thus the resolution increases from 8.37 pF to 7.28 pF on increasing the length.

4. SENSITITVITY:-

The sensitivity of the concentric cylinder capacitor is given by the equation

$$dC/d\varepsilon = 2\pi\varepsilon_0 l/\log(R1/R2)$$

ε_0 = permittivity of the air

l = length of the each plate

R1 = inner diameter of outer cylinder

R2 = outer diameter of inner cylinder

The sensitivity of the capacitor is equal to 6.054 pF.

Thus the sensitivity of the capacitor remains same on increasing the thickness.

3. ROD ELECTRODE CAPACITOR:-

1. EFFECT OF THE VARIATION OF LENGTH:-

The length of the rod electrode capacitor is varied and its effect on the parameters is measured.

1. ELECTRIC FIELD:-

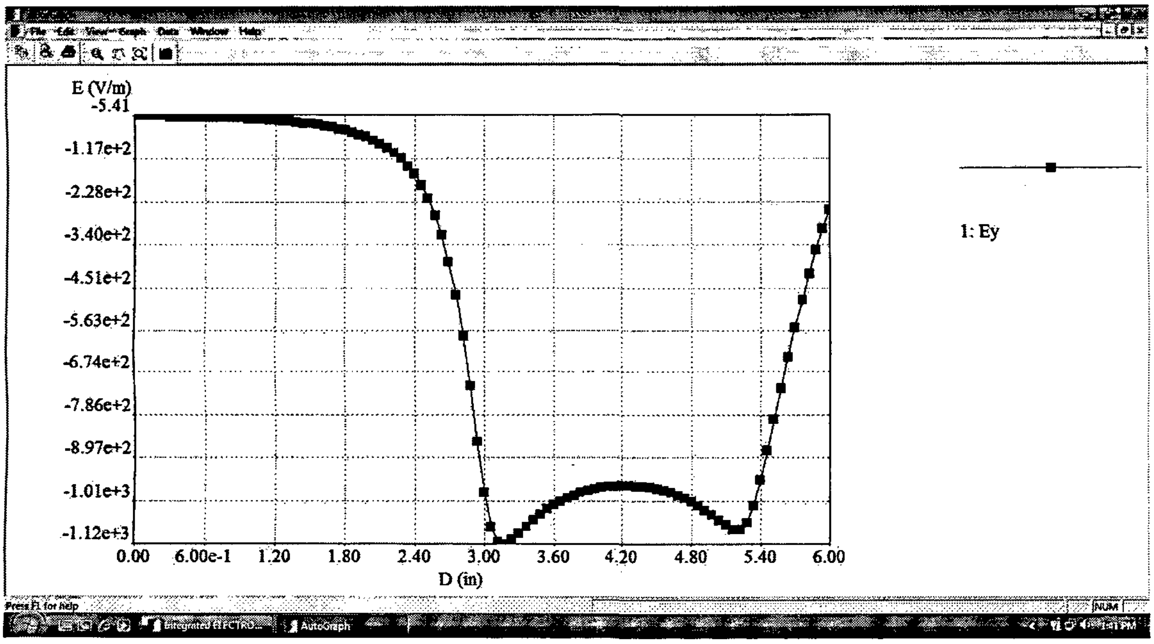


Fig.4.12 Electric field vs distance

The length of the single rod electrode of the capacitor is increased from 2.5 inch to 2.8 inch and changes in the electric field are measured. The electric field in the region along the length of the single rod electrode is less stable and constant similar to the electric field for the original length. The electric field for single rod electrode is higher than the electric field for the original length. The electric field for the single rod electrode decreases from -1.12 kV/m to -0.954 kV/m between the points 3.15 inch and 4.30 inch and then increases to -1.07 kV/m between the points 4.30 inch and 5.25 inch.

2. ELECTRIC FIELD OUTSIDE AND NEAR TO THE EDGE OF ELECTRODES:-

The fringing field varies in the range of -1.12 kV/m to -5.41 V/m when the distance is varied in x-axis between 3.15 inch to 0 inch on one side of the rod and -1.07 kV/m to -5.41 V/m when distance is varied in x-axis between 5.25 inch and 8.30 inch on other side of rod.

2. CAPACITANCE:-

The charge accumulated in each plate of the capacitor is 53 pC when the dielectric medium is air.

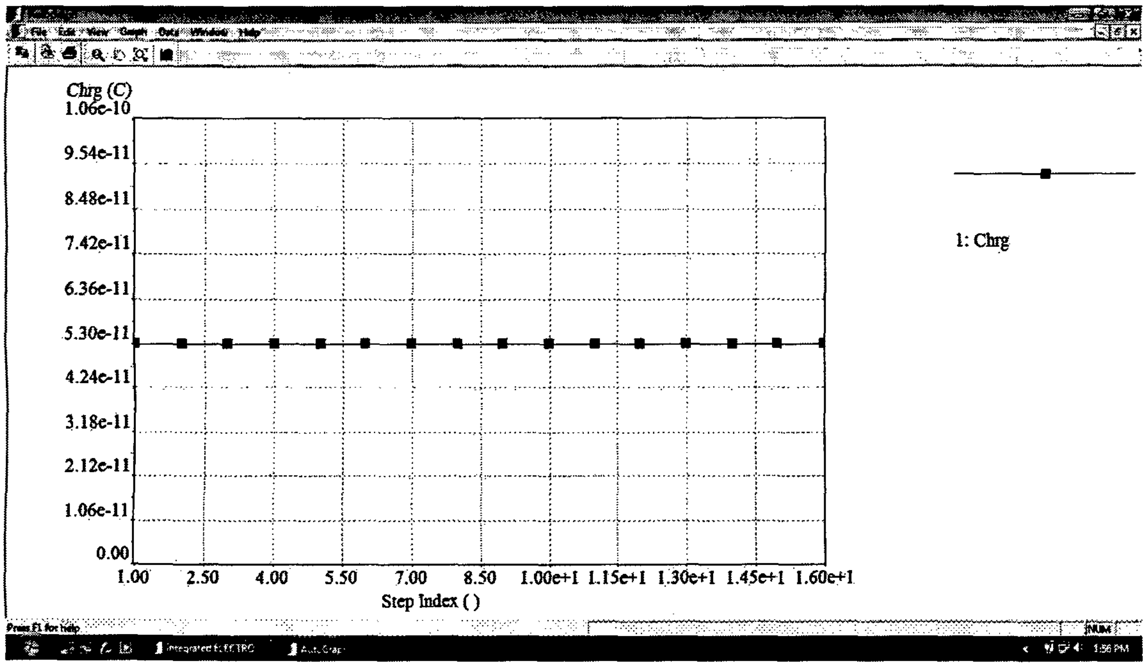


Fig.4.13 Capacitance vs gap

3. RESOLUTION:-

The minimum charge accumulated on single rod electrode is 53 pC when the dielectric medium is air at the voltage of 30 V. The capacitance of the rod electrode capacitor is obtained as 34.54 pF. Thus the resolution of the capacitor for the dielectric medium of air is 34.54 pF. Thus the resolution of the capacitor decreases on increasing the length.

4. EFFECT OF THE VARIATION OF DIAMETER:-

The diameter of the rod electrode capacitor is varied and its effect on the parameters is measured.

1. ELECTRIC FIELD:-

The diameter of the single rod electrode of the capacitor is increased from 0.5 inch to 0.9 inch and changes in the electric field are measured. The electric field in the region along the length of the single rod electrode is more stable and constant as compared to the electric field for the original length. The electric field for single rod electrode is lower than the electric field for the original length. The electric field for the single rod electrode is 0.388 V/m.

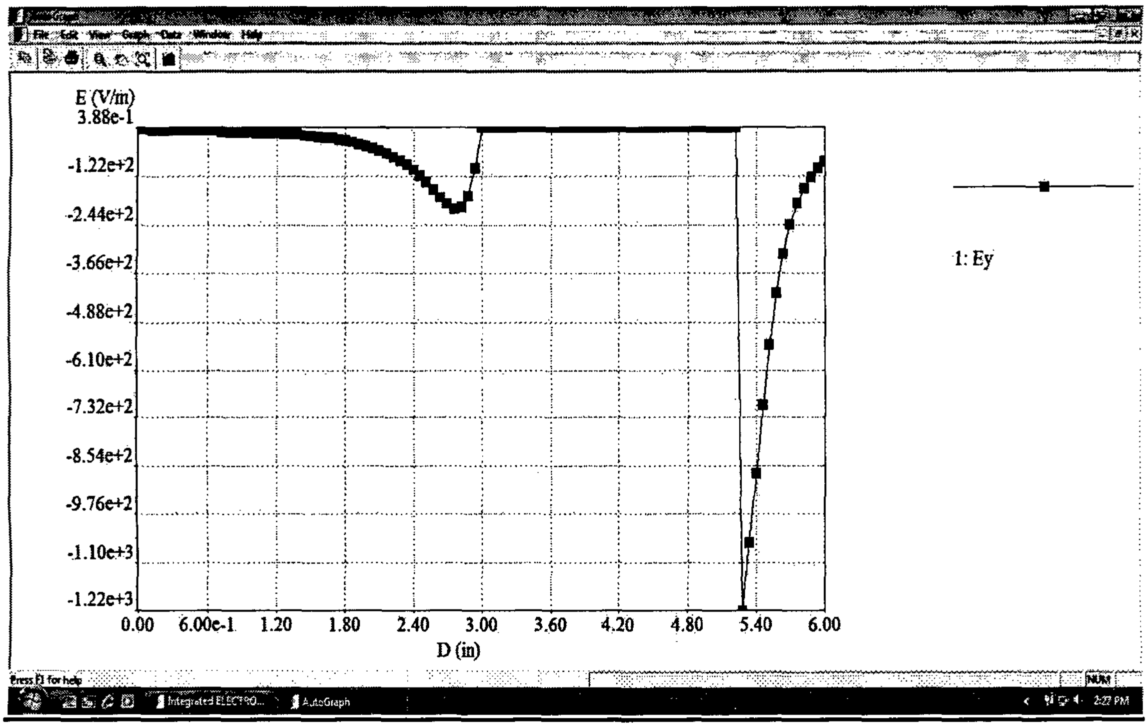


Fig.4.14 Electric field vs distance

2. ELECTRIC FIELD OUTSIDE AND NEAR TO THE EDGE OF ELECTRODES:-

The fringing field increases in the range of 0.388 V/m to -0.214 kV/m when the distance is varied in x-axis between 3 inch to 2.73 inch and then decreases to 0.388 kV/m when the distance is varied between 2.73 inch to 0 inch. The electric field decreases in the range of -1.22 kV/m to -0.071 kV/m when the distance is varied between 5.40 inch and 6 inch.

3. CAPACITANCE:-

The charge accumulated in each plate of the capacitor is 65 pC when the dielectric medium is air.

4. RESOLUTION:-

The minimum charge accumulated on single rod electrode is 65 pC when the dielectric medium is air at the voltage of 30 V. The capacitance of the rod electrode capacitor is obtained as 42.36 pF. Thus the resolution of the capacitor for the dielectric medium of air is 42.36 pF. Thus the resolution of the capacitor decreases on increasing the width.

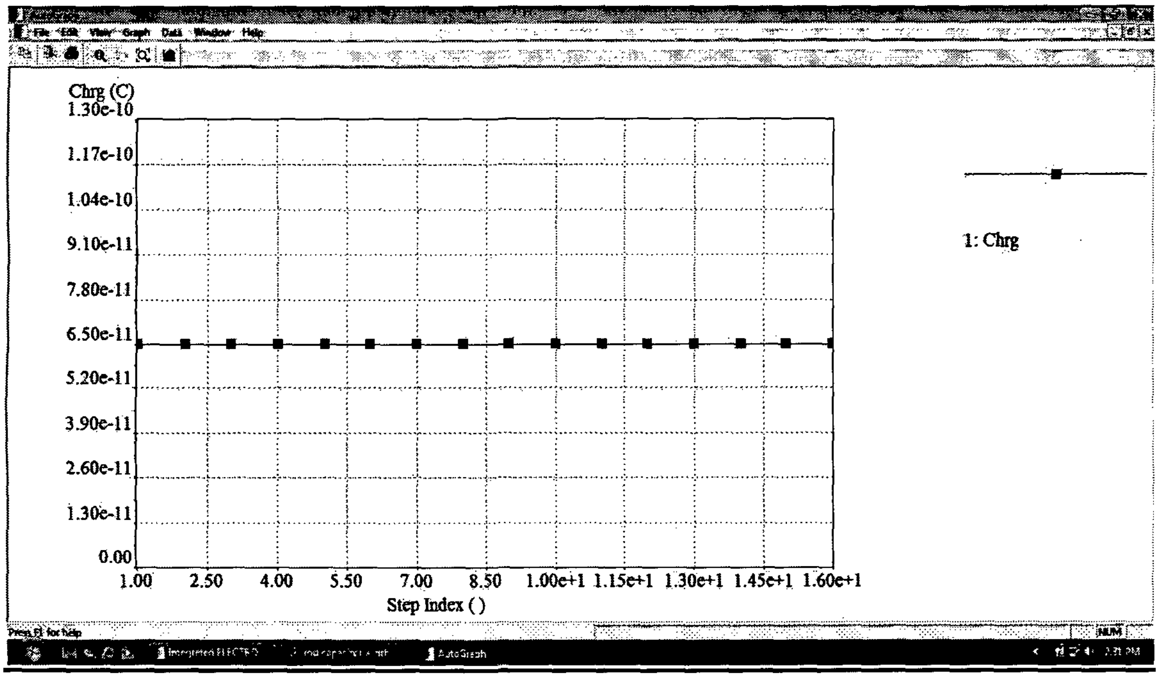


Fig.4.15 Capacitance vs gap

4.6 RESULTS AND CONCLUSION:-

The parallel plate capacitor has the resolution of 8.69 pF near to the resolution of 8.37 pF of concentric cylindrical capacitor and highest sensitivity of 4.164 pF. The electric field between the electrodes is stable, constant and highest equal to 3.94 kV/m. Though the fringing electric field of parallel plate capacitor is highest equal to 5.86 kV/m but the rate of the change of fringing electric field with distance is also highest -2.02 kV/m. Thus the parallel plate capacitor is used for making electrodes of the capacitive sensor.

CHAPTER 5

PROPOSED PROBE DESIGN

The capacitive sensor probe consists of the following components:-

5.1 TWO PARALLEL PLATE CAPACITORS:-

Two parallel plate capacitors are kept perpendicular to each other measuring the soil moisture content in the same volume of the soil[9]. The capacitors are made of aluminium metal. The dimensions of the capacitor are:-

1. Length of the electrode – 100 mm.
2. Width of the electrode – 15 mm.
3. Thickness of the electrode – 1 mm.
4. Gap between the electrodes – 20 mm.

The parameters of the capacitor are:-

1. ELECTRIC FIELD:-

The electric field in two regions has been taken into consideration.

1. ELECTRIC FIELD IN THE REGION BETWEEN ELECTRODES:-

The electric field per unit length of the electrode in the region between the electrodes is stable, constant and very high 3 kV/m. The electric field increases with increase in length thus the length of the capacitor is kept 100 mm. The electric field increases with decrease in the thickness thus the thickness is kept 1 mm. The electric field increases with decrease in the gap between the two electrodes thus the gap is kept 20 mm. Thus a very high, stable and constant electric field in the region between the electrodes increases the accuracy and sensitivity of the capacitive sensor. Because of the high and constant electric field in the region between the electrodes the electric field due to enviromental noise will disorientate the dipoles less and thus increasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will be changed to the original orientation of the dipoles in the direction of the electric field and thus increasing the sensitivity of the capacitive sensor.

2. ELECTRIC FIELD IN THE REGION OUTSIDE AND NEAR TO THE EDGE OF THE ELECTRODES:-

The electric field outside and near to edge of the electrodes is the fringing electric field. This fringing electric field acts as enviromental noise interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the readings.

The fringing field varies in the range of 3 kV/m to 0.066 kV/m when the distance is varied in x-axis between 108 mm to 0 inch. Thus the rate of change of the fringing field is 6.4 kV/m inch. Thus the fringing electric field decreases to zero at less distance and the other components are less interfered.

2. CAPACITANCE:-

The charge accumulated in each plate of the capacitor is 3.48 nC when the dielectric medium is air.

3. RESOLUTION:-

The minimum charge accumulated on each plate is 3.48 nC per unit width when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 0.87 pF. Thus the resolution of the capacitor for the dielectric medium of air is 0.87 pF.

4. SENSITIVITY:-

The sensitivity of the parallel plate capacitor is given by the equation

$$dC/d\varepsilon = \varepsilon_0 A/d$$

ε_0 = permittivity of the air

A = area of the each plate

d = gap between the plates

The sensitivity of the capacitor is 0.17 pF.

5.2 PLASTIC SPACER:-

A 25 mm plastic spacer is used in order to change the length of the electrodes from 100 mm to 75 mm. Thus the soil moisture sensing is carried out with electrodes with two different lengths.

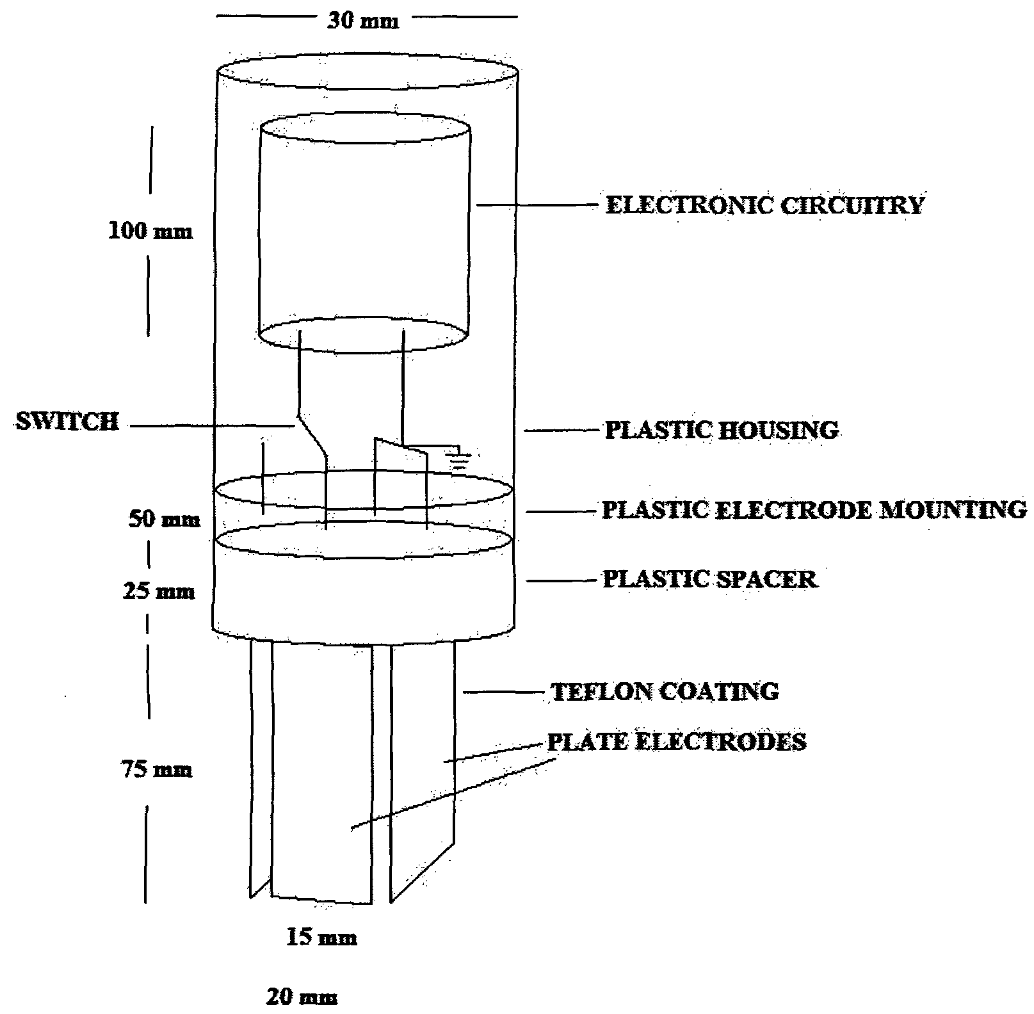


Fig.5.1 Capacitive probe sensor

5.3 PLASTIC ELECTRODE MOUNTING:-

A 50 mm plastic electrode mounting is used to hold the electrodes. The electrodes are attached to it.

5.4 PLASTIC HOUSING:-

A 100 mm plastic housing is used to contain the electronic circuitry in it. The connection cables from the capacitor are connected to the electronic circuitry and the connection cables from the electronic circuitry are connected to the data logging system for further processing of the data.

The outer surface and the edges of the plates of the capacitors are coated with an insulating material with low dielectric constant in order to reduce the effects of the fringing electric field due to the edges of the plates, electric field due to the charge accumulated on the outer surface of the plates[10], the electric field in the enviroment. The fringing electric field due to the edges of the plates causes induction of charges in the pair of the plates of the second capacitor. This causes an error in the capacitance of the second capacitor. This fringing electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field due to the charge present on the outer surface of the plates causes an interference in other nearby components of the sensor. This electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field present in the environment[11] causes an interference with the capacitor. This electric field is reduced by the Teflon coating due to its less dielectric constant.

5.5 PROPERTIES OF THE TEFLON:-

The following properties of teflon make it to be used for coating the outer surface of the plates of the parallel plate capacitive sensor.

1. **RESISITANT TO MANY MATERIALS:-**

   This includes ozone, chlorine, acetic acid, ammonia, sulfuric acid and hydrochloric acid. The only chemicals known to affect these coatings are molten alkali metals and highly reactive fluorinating agents. Thus Teflon will be affected less by the chemicals and ionic solutions present in the soil.

2. **WEATHER AND UV RESISTANCE:-**

   The Teflon coated plates will more resistant to weather. Thus the Teflon coated plates have long endurance and durability.

3. **NON STICK:-**

   Very few solid substances will permanently adhere to a Teflon coating. While tacky materials may show some adhesion, almost all substances release easily. Thus the soil and other chemicals will not be able to adhere to Teflon coated plates.

4. **OUTSTANDING PERFORMANCE AT THE HIGHER TEMPERATURES:-**

   It can temporarily withstand temperatures of 260C and cryogenic temperatures of -240C and still have the same chemical properties. It has an initial melting point of 342C (+- 10C) and a secondary melting point of 327C (+- 10C). Thus Teflon coated plates will be able to operate at higher temperatures.

5. **LOW COEFFICIENT OF FRICTION:-**

   It is the ratio of the force required to make two surfaces slide over each other. A low number equals low resistance and smooth operation. This indicates the difficulty in sliding one surface against another. The coefficient of friction is generally in the range of 0.05 to 0.20, depending on the load, sliding speed, and type of Teflon coating used. Thus the Teflon coated plates can be penetrated easily into the soil.

6. **NON WETTING:-**

Teflon finishes are both hydrophobic and oleophobic, cleanup is easier and more thorough. Thus the error in the capacitance due to moisture will be less.

7. **EXCEPTIONAL DIELECTRIC PROPERTIES:-**

Teflon has a high dielectric strength over many different frequencies, low dissipation factor and high surface resistivity. Dielectric strength is the high voltage that the insulating material can withstand before it breaks down. In addition it has a low dissipation factor; this is the percentage of electrical energy absorbed and lost when current is applied to an insulating material. A low dissipation factor means that the absorbed energy dissipated as heat is low. The high surface resistivity refers to the electrical resistance between opposite edges of an unit square on the surface of an insulating material. The fringing electric field due to the edges of the plates causes induction of charges in the pair of the plates of the second capacitor. This causes an error in the capacitance of the second capacitor. This fringing electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field due to the charge present on the outer surface of the plates causes an interference in other nearby components of the sensor. This electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field present in the environment[12] causes an interference with the capacitor. This electric field is reduced by the Teflon coating due to its less dielectric constant.

5.6 COMPARATIVE CHART OF DIFFERENT COATING MATERIALS:-

Materials / Properties	TEFLON	POLYSTYRENE	FIBRE GLASS	POLYESTER	POLYURETHAN
Upper use temperature (^0C)	285	240	2000	260	140

Thermal stability (^{0}C)	360	80	230	275	100
Thermal expansion (ppm/^{0}C)	80	158	258.33	123.5	100-200
Water absorption	No	Less	Less	Less	Less
Weatherability	Outstanding	Good	Good	Good	Good
Tensile modulus (MPa)	950-2150	0.331-320	55	0.7	39.99
Resistance to chemical attack	Excellent	Good	Good	Good	Good
Dielectric constant	1.89-1.93	2.6	3.09	4	4.7

SPECIFICATIONS OF THE CAPACITIVE PROBE SENSOR:-

1. RESOLUTION OF THE PROBE CAPACITOR IN THE AIR:-

The resolution of the probe capacitor in the air is

$$C = \varepsilon_0 \, A/d$$

$$= \frac{8.85*10^{-12}*100*15*10^{-6}}{25*10^{-3}}$$

$$= 0.66 \text{ pF}$$

2. SWING IN THE MOISTURE CONTENT θ_v:-

$$0 <= \theta_v < 1$$

$$\varepsilon = \varepsilon_w * \theta_v + \varepsilon_s * \theta_s$$

$$\varepsilon = \varepsilon_w * \theta_v + \varepsilon_s * (1 - \theta_v)$$

$$\varepsilon = (\varepsilon_w - \varepsilon_s) * \theta_v + \varepsilon_s$$

$$\varepsilon = (80 - 4) * \theta_v + 4$$

$$\varepsilon = 76 * \theta_v + 4 \qquad (1)$$

$$\theta_v = 0$$

$$\varepsilon_{min} = 4$$

$$\theta_v = 1$$

$$\varepsilon_{max} = 80$$

3. SWING IN THE CAPACITANCE:-

$$C_{min} = \varepsilon_{min} A/d$$

$$= \frac{4*8.85*10^{-12}*100*15*10^{-6}}{25*10^{-3}}$$

$$= 2.66 \text{ pF}$$

$$C_{max} = \varepsilon_{max} A/d$$

$$= \frac{80*8.85*10^{-12}*100*15*10^{-6}}{25*10^{-3}}$$

$$= 53.1 \text{ pF}$$

4. SWING IN THE FREQUENCY:-

$$f_{max} = \frac{1}{2\pi*\text{sqrt}(15.47*10^{-6}*\frac{100*10.66*10^{-24})}{110.66*10^{-12}}}$$

$$= 56.8 \text{ MHz}$$

$$f_{min} = \frac{1}{2\pi*\text{sqrt}(15.47*10^{-6}*\frac{100*0.66*10^{-24})}{100.66*10^{-12}}}$$

$$= 50 \text{ MHz}$$

5. SENSITIVITY OF THE PROBE CAPACITOR:-

The sensitivity of the parallel plate capacitor is given by the equation

$$dC/d\varepsilon = \varepsilon_0 A/d$$

ε_0 = permittivity of the air

A = area of the each plate

d = gap between the plates

The sensitivity of the capacitor is 0.17 pF.

6. ACCURACY OF THE OSCILLATOR:-

The average error in the frequency of oscillation is 2.34 MHz. Thus the accuracy of the oscillator is 4.68% at 50 MHz.

7. RESOLUTION OF THE OSCILLATOR:-

The oscillator operates in the frequency range of the 50 to 56.8 MHz. Thus the resolution of the oscillator is given by

$$C1 = \frac{C2}{C2\,(2\pi f)^2 L - 1} - 99.34$$

$$= \frac{100*10^{-12}}{100*10^{-12}(2\pi*52.91*10^{6})^{2}*0.15*10^{-6} - 1} - 99.34$$

$$= 0.66 \text{ pF}$$

8. SENSITIVITY OF THE OSCILLATOR:-

The sensitivity of the oscillator is given by

$$df/dC1 = \frac{-1}{4\pi*\mathrm{sqrt}(C1^{3}(C1+C2)/C2)}$$

$$= \frac{-1}{4\pi*\mathrm{sqrt}((0.66*10^{-12})^{3})(0.66*10^{-12}+100*10^{-12})/100*10^{-12})}$$

$$= -0.148 \text{ MHz/pF}$$

5.8 CAPACITOR PROBE SENSOR DESIGN FOR HARDWARE IMPLEMENTATION

The capacitive probe sensor[13][14] is designed in the Inventor software and modifications are done on it for making the hardware implementation of the capacitive probe sensor. The various components of the capacitive probe sensor are designed in the

Inventor software for their hardware implementation. The capacitive probe sensor consists of following components:-

1. PLASTIC ELECTRODE HOLDER:-

A plastic electrode holder is used to hold the aluminium electrodes parallel to each other and prevents the electrodes from moving from their positions when the capacitive probe sensor is dipped into the soil. Thus the electrode holder keeps the gap between the electrodes constant. The plastic electrode holder is made of delirin material having low dielectric constant of 3.7.

Two types of plastic holders are used for holding the electrodes with a gap of 20 mm and 40 mm.

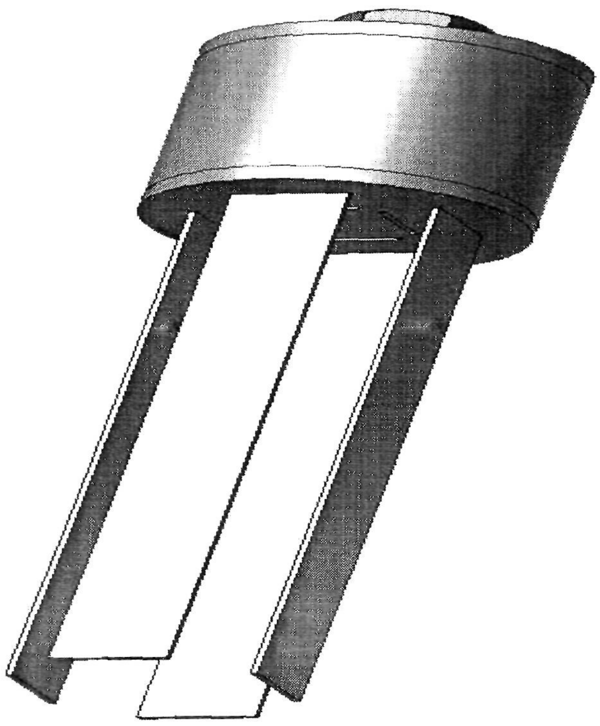


Fig.5.2 Capacitive probe sensor

1. PLASTIC CYLINDRICAL HOUSING:-

A plastic cylindrical housing is used to contain the plastic electrode holder and the connection cables connecting the electrodes to the impedance/spectrum analyzer. The plastic cylindrical housing prevents the contact of the plastic electrode holder and connection cables with moisture. The plastic cylindrical housing is made of the material of delirin.

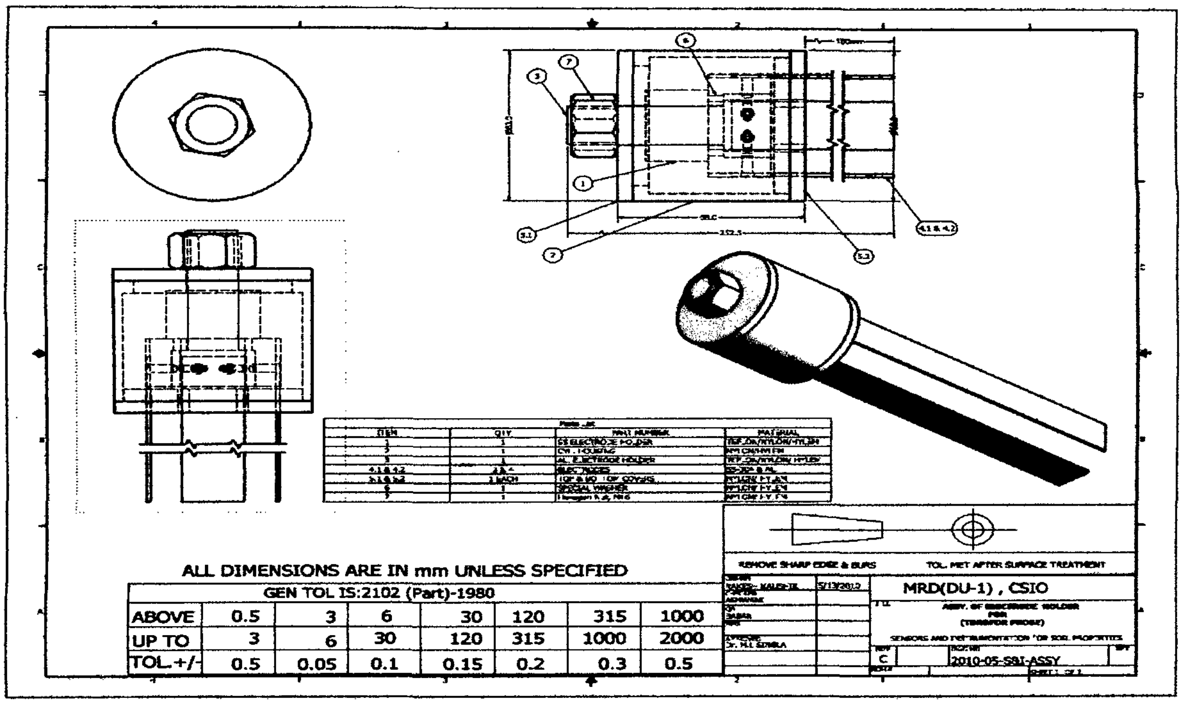


Fig. Assembly of the capacitive probe sensor

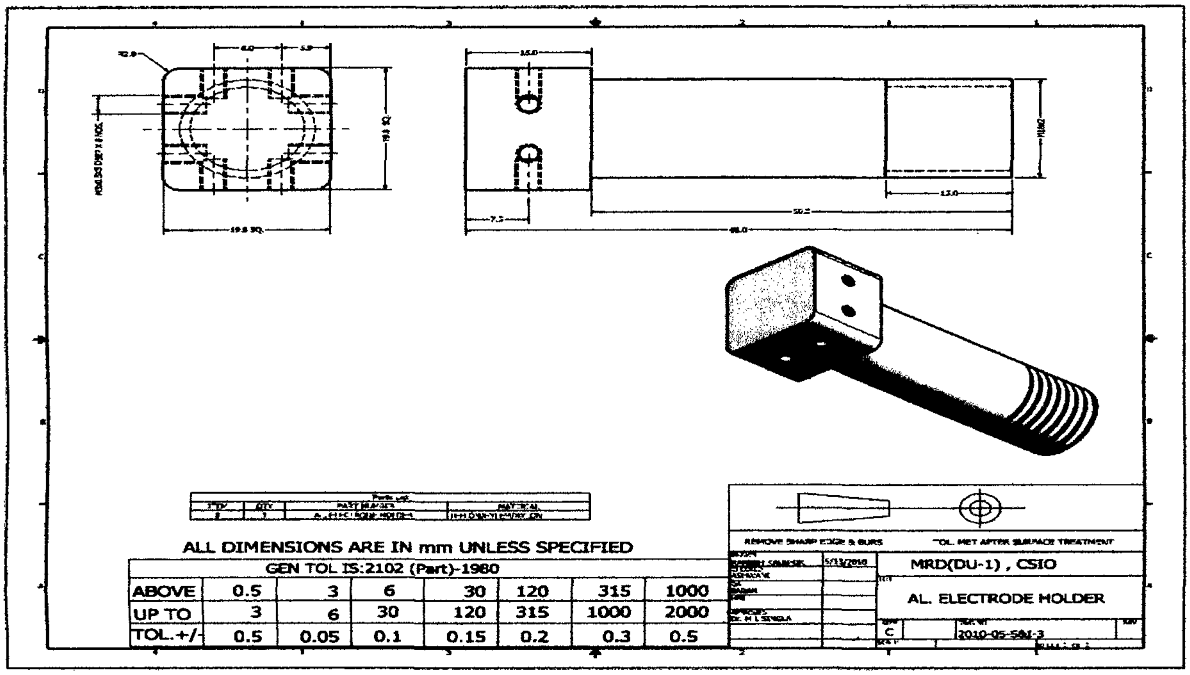


Fig.5.3 Plastic electrode holder

1. PLASTIC TOP COVER OF THE PLASTIC CYLINDRICAL HOUSING:-

The plastic cylindrical housing is covered from the top by a plastic top cover. The plastic top cover prevents the contact of the plastic electrode holder and connection cables with moisture and other enviromental materials. The plastic top cover is made of the material of delirin.

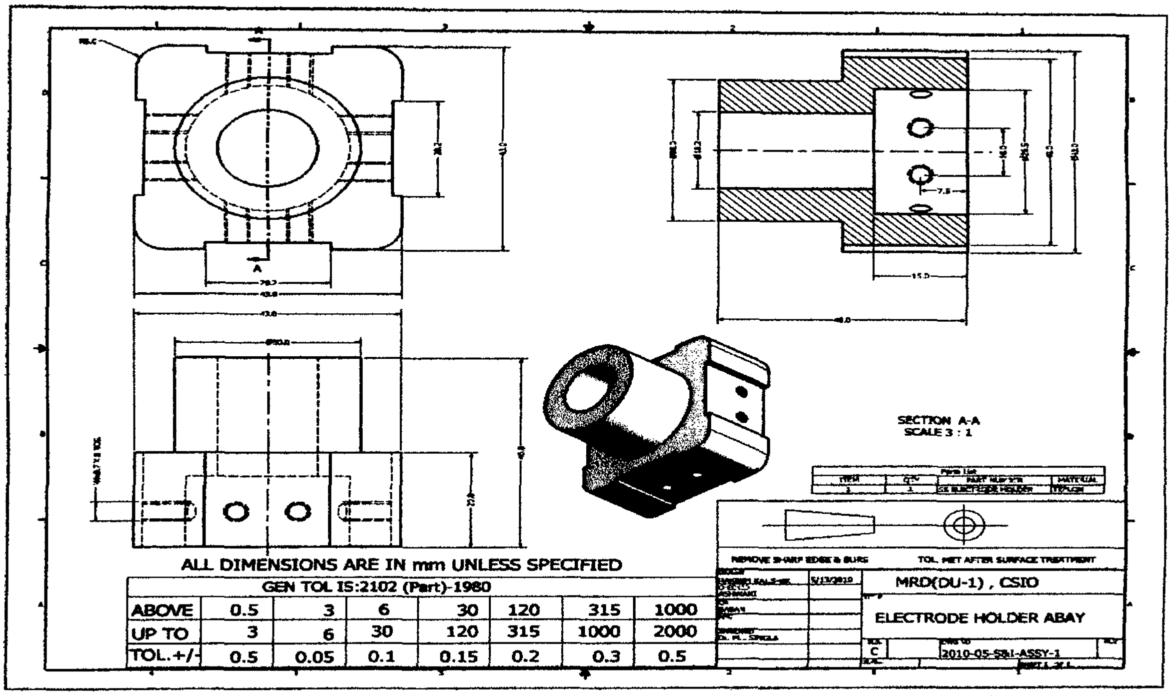


Fig.5.4 Plastic electrode holder

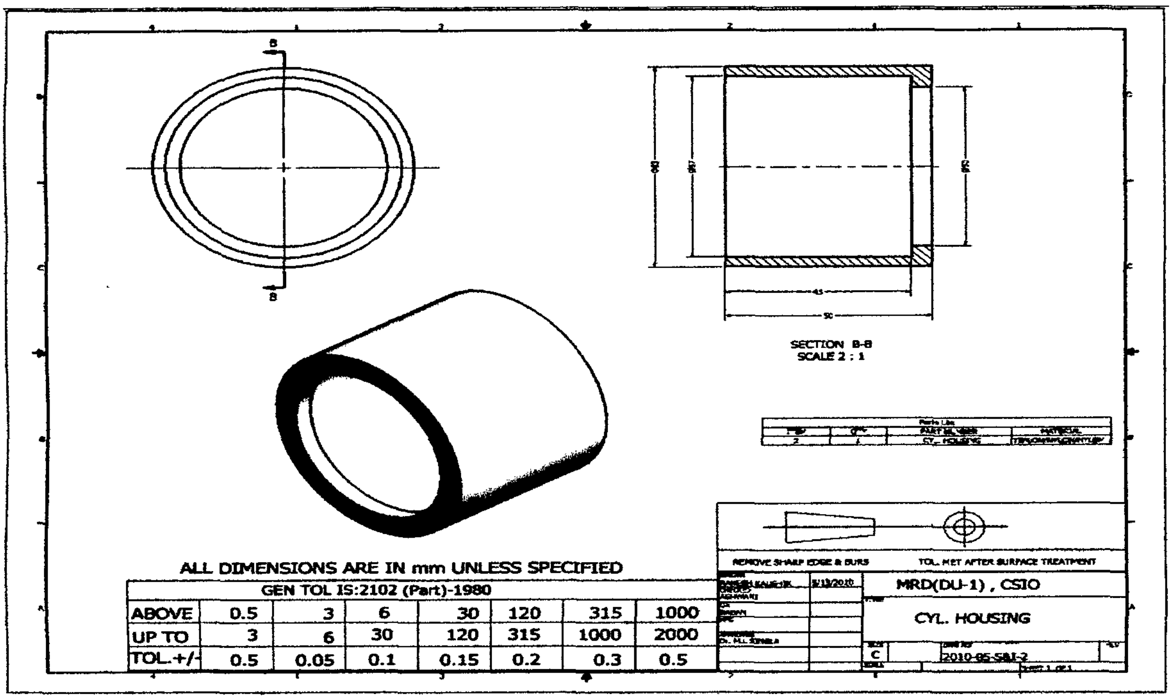


Fig. 5.5 Plastic cylindrical housing

1. PLASTIC BOTTOM COVER OF THE PLASTIC CYLINDRICAL HOUSING:-

The plastic cylindrical housing is covered from the bottom by a plastic bottom cover. The electrodes pass through the plastic bottom cover. The plastic bottom cover prevents the contact of the plastic electrode holder and connection cables with moisture and other enviromental materials. The plastic bottom cover is made of the material of delirin.

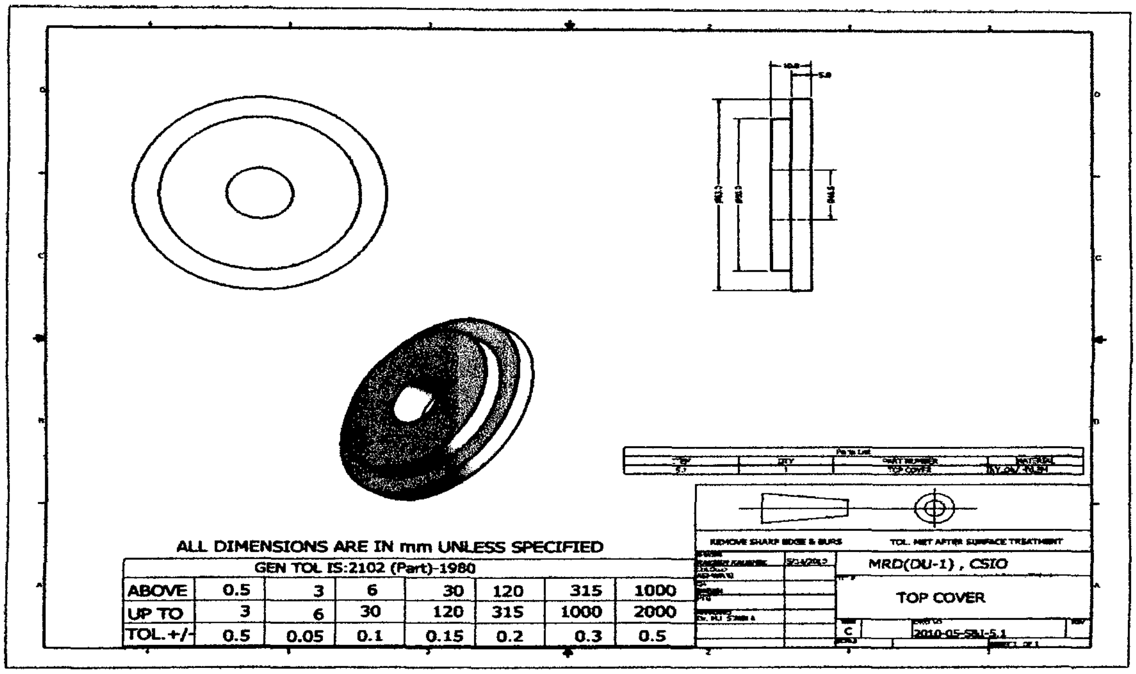


Fig.5.6 Plastic top cover

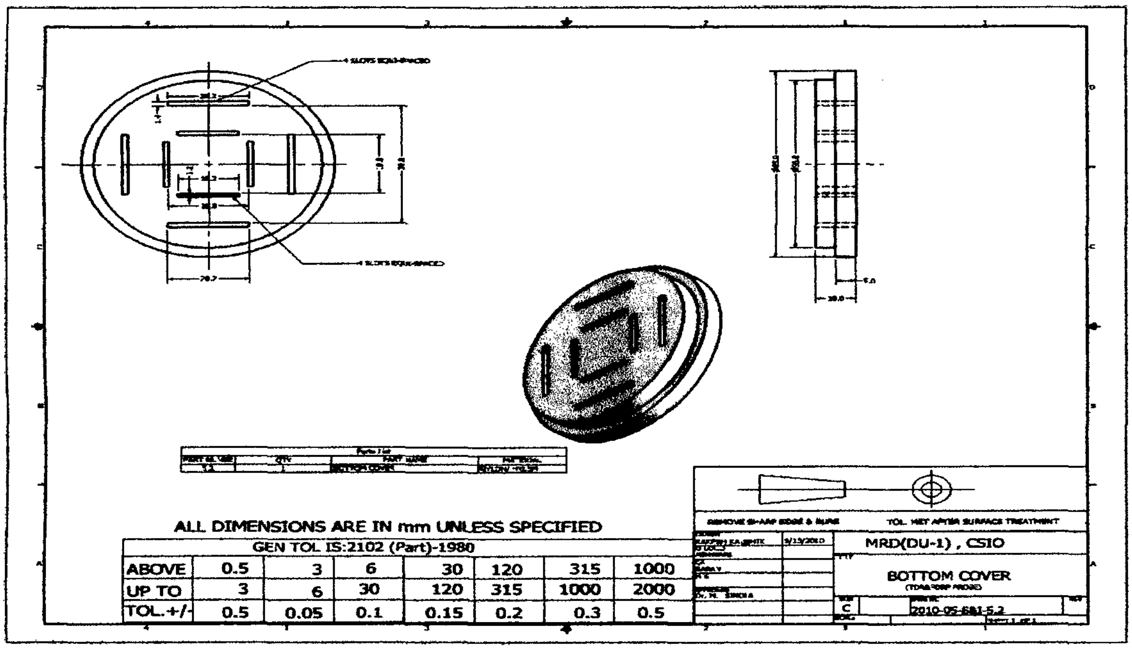


Fig.5.7 Plastic bottom cover

2. <u>PLASTIC SPECIAL WASHER:-</u>

A plastic special washer is used between the plastic electrode holder and plastic top cover of the plastic cylindrical housing to hold the plastic electrode holder inside the plastic cylindrical housing. The plastic special washer is made of the material of delirin.

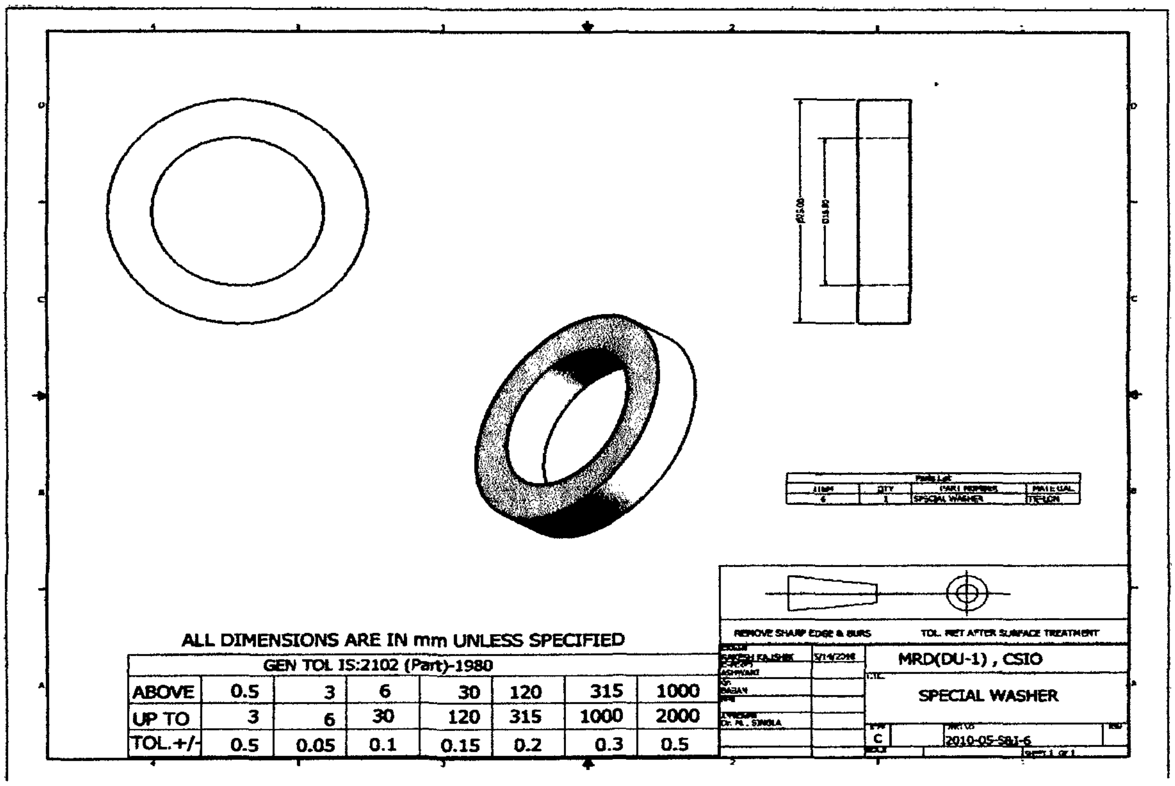


Fig.5.8 Plastic special washer

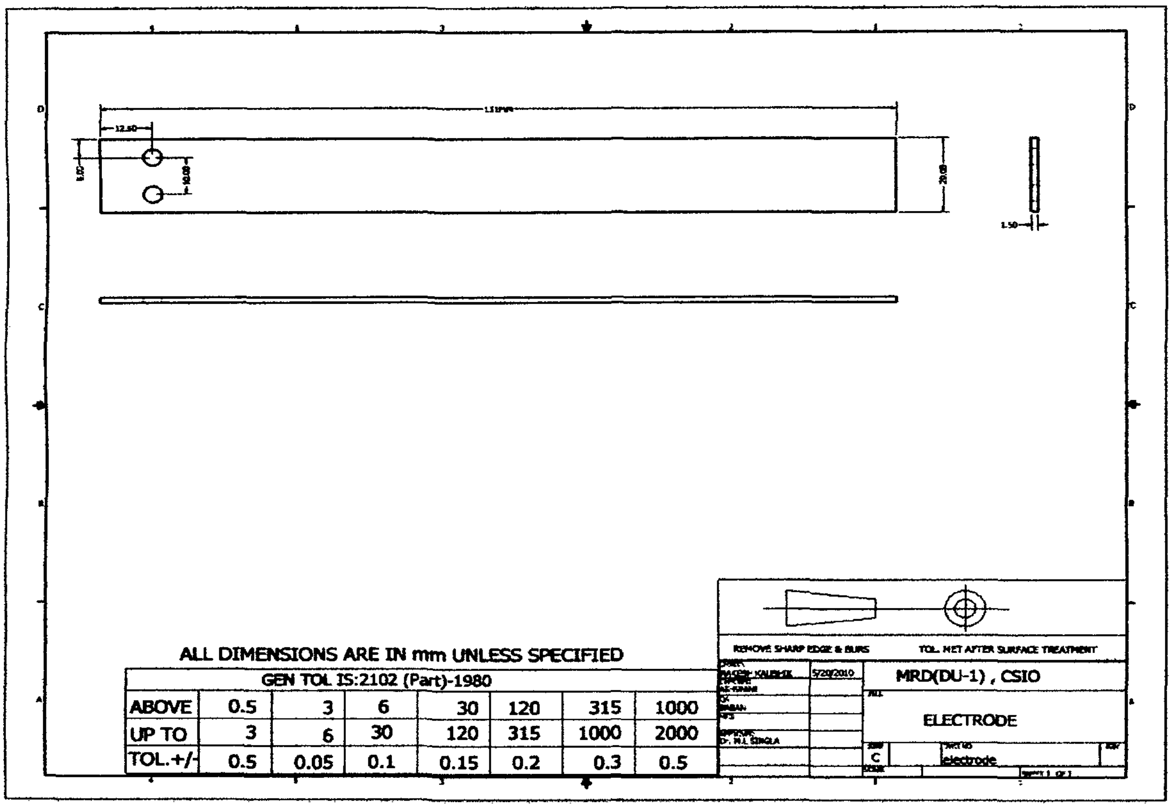


Fig.5.9 Electrodes

CHAPTER 6

COLPITTS OSCILLATOR DESIGN

6.1 SIMULATION OF THE COLPITTS OSCILLATOR FOR ITS EFFECTIVE IMPLEMENTATION:-

The Colpitts oscillator design[15][16] used for the sensor implementation works at the frequency of 50MHz while an oscillator that can generate sinusoidal waves of upto 1.024GHz is required initially for sensor implementation. Previously an oscillator that can generate sinusoidal waves upto 1.024 GHz was required. Thus the possibility of the effective implementation of the oscillator for 1.024 GHz in hardware is determined through simulation of the Colpitts oscillator in TINA PRO 7.0 simulation software.

6.2 CALCULATION OF OSCILLATION FREQUENCY FOR COLPITTS OSCILLATOR:-

The Colpitts oscillator circuits used above consists of two capacitors- one of constant value 100pF and other, part of capacitive probe sensor, is having value of 0.16pF without any dielectric medium and one inductor of constant value 0.15μH forming an LC tank circuit.

Thus we have

C1=0.16pF

C2=100pF

L=0.15 μH

Thus C is given by,

C=(C1*C2)/(C1+C2)

C=(100*0.16*10^-24)/(100.16*10^-12)

or C=0.16pF

Thus,

f= 1/(2*3.14*(0.16*0.15*10^-18) ½)

or f=1.027GHz

6.3 SIMULATION RESULTS OBTAINED FOR THE COLPITTS OSCILLTOR FOR ITS SUITABILITY FOR EFFECTIVE SENSOR IMPLEMENTATION:-

The Colpitts oscillator design used for the sensor implementation works at the frequency of 50MHz while an oscillator that can generate sinusoidal waves of upto 1.024GHz is required initially for sensor implementation. Thus the oscillator design is implemented practically through TINA pro software tool and the oscillator design is simulated in the TINA pro. The output frequency of the oscillator is given by equation

$$f_0 = \frac{1}{2\pi\sqrt{L \cdot \left(\frac{C_1 \cdot C_2}{C_1 + C_2}\right)}}$$

where the series combination of C1 and C2 creates the effective capacitance of the LC tank.

Real circuits will oscillate at a slightly lower frequency due to junction capacitances of the transistor and possibly other stray capacitances.

The capacitor C1 is the capacitive sensor used to sense the soil moisture. As C1 is decreased from the value of 100pF to lower values the frequency of oscillation increases from 50MHz to higher values. As the value of the capacitor is decreased to 0.16pF the output frequency of oscillation increases to 1.024GHz. The practical variation of the frequency is measured through the simulation. The simulation results obtained gives the actual variation of the frequency with the capacitance and differences of the actual values from the theoretical values.

VARIATION IN THE FREQUENCY OF OSCILLATION THEORETICALLY AND PRACTICALLY THROUGH SIMULATION:-

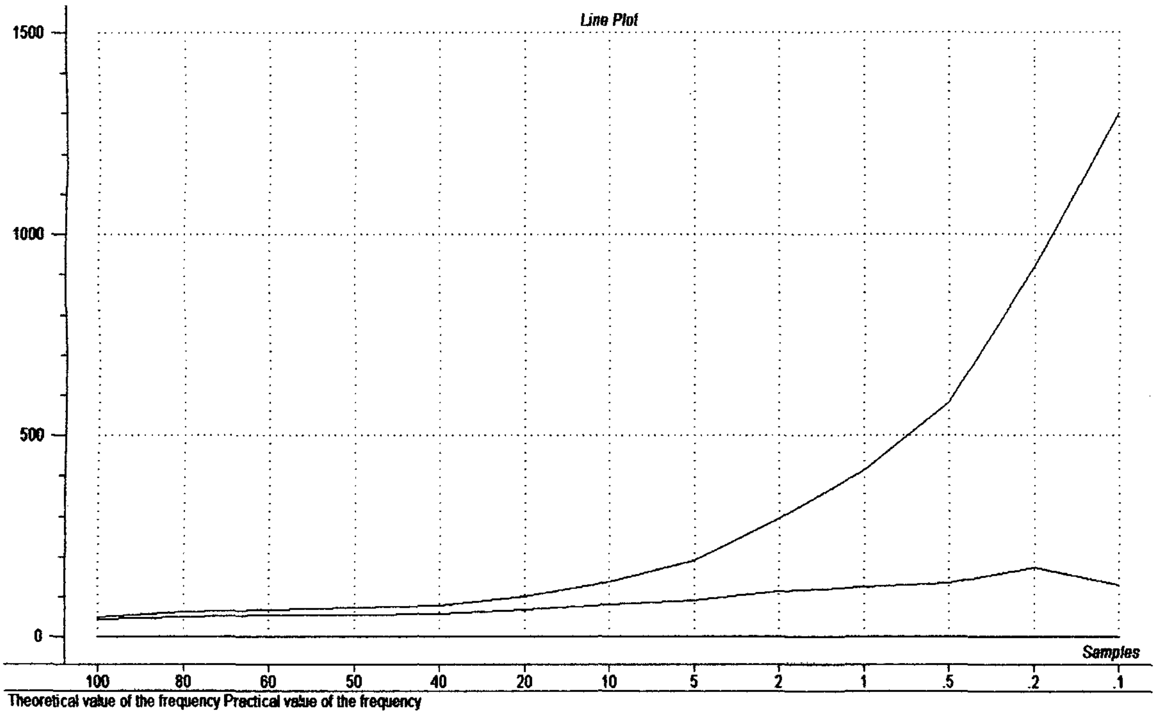


Fig.6.1 Frequency vs capacitance for transistor BC547 for frequencies less than 1.024 GHz

Frequency (MHz) / Capacitance(pF)	Theoretical value of the frequency	Practical value of the frequency
100	50	44.44
80	61.67	48.48
60	67.14	53.33
50	71.21	55.17
40	76.91	57.14
20	100.71	66.67
10	136.36	80
5	188.41	88.89
2	293.61	114.28
1	413.19	122.27
0.5	582.89	133.37
0.2	920.26	172.86
0.1	1300.30	128.04

<u>VARIATION IN THE FREQUENCY OF OSCILLATION THEORETICALLY AND PRACTICALLY THROUGH SIMULATION FOR TRANSISTOR QN2222A:-</u>

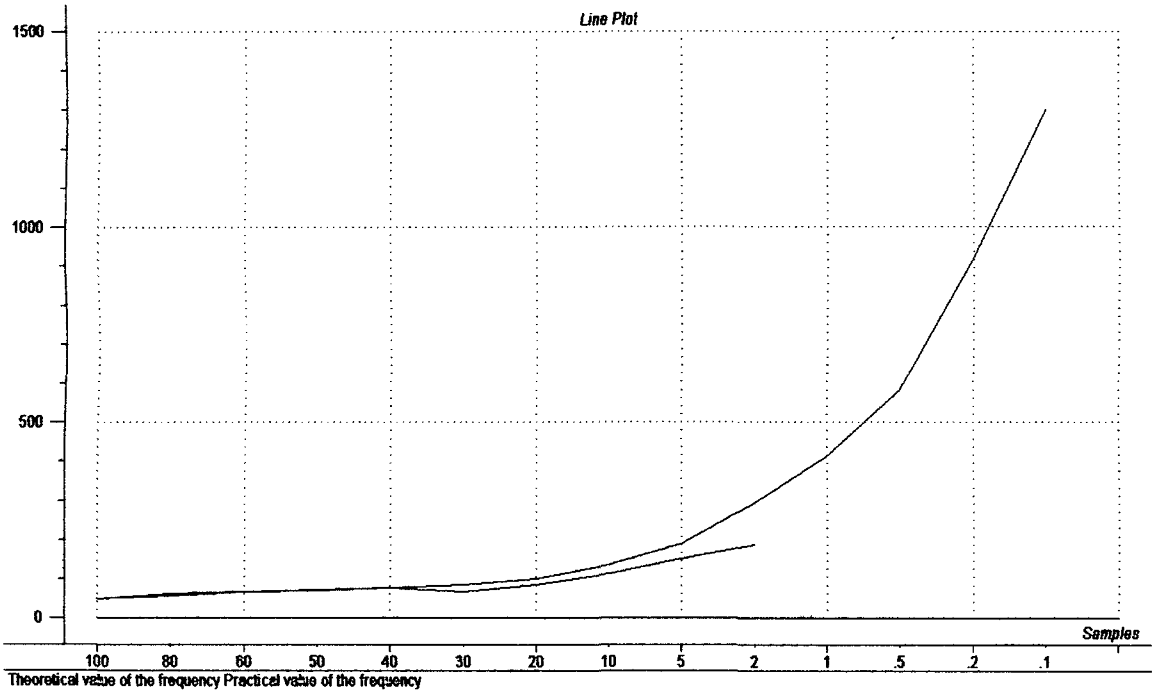


Fig.6.2 Frequency vs capacitance for frequencies less than 1.024 GHz for transistor QN2222A

The values that are obtained theoretically by the equation for the frequency of oscillation are much different as obtained practically from the simulation. There are two reasons for this variation. The first reason for such variation is the type of the transistor used in the oscillator circuit. The transistor used is BC547. The transistor is changed to QN2222A. The following values of the frequency of oscillation are obtained:-

Frequency (MHz) / Capacitance(pF)	Theoretical value of the frequency	Practical value of the frequency
100	50	49.23
80	61.67	57.14
60	67.14	66.67
50	71.21	68.97
40	76.91	76.19
30	85.59	66.67
20	100.71	84.21
10	136.36	114.29
5	188.41	152.38
2	293.61	188.24
1	413.19	OUTPUT NOT STABLE
0.5	582.89	OUTPUT NOT STABLE
0.2	920.26	OUTPUT NOT STABLE
0.1	1300.30	OUTPUT NOT STABLE

The values of the frequency of oscillation obtained theoretically and practically are still much different. The reason for such variation is the type of transistor. The following transistors are used and the value of frequency of oscillation is obtained at 100pf. The value of the frequency of oscillation obtained is much close to 50MHz so the transistors can be used for implementation of oscillator.

1. MMBT 2369LT1
2. MPQ6700
3. MPS2712
4. MPS3826
5. MPS6544
6. MPS6546
7. MPS6547

8. MPS6548
9. MPS706A
10. MPS8099

The transistor MMBT 2369LT1 is used. The oscillator design is used for frequencies less than 50MHz because the output of the oscillator is stable and close to the theoretical values for frequencies less than 50MHz. Thus the capacitance is increased from 100pF to higher values.

VARIATION IN THE FREQUENCY OF OSCILLATION THEORETICALLY AND PRACTICALLY THROUGH SIMULATION FOR TRANSISTOR MMBT 2369LT1:-

Frequency (MHz) / Capacitance (pF)	Theoretical value of the frequency	Practical value of the frequency	Error in the frequency
100	50	55.17	-5.17
110	56.8	54.05	2.03
115	56.22	53.33	2.89
120	55.67	53.33	2.34
125	55.16	53.33	1.83
130	54.69	52.46	2.23
135	54.25	51.46	2.79
140	53.83	51.48	2.35
145	53.44	51.28	2.16
150	53.03	51.28	1.75
155	52.74	50	2.74
160	52.41	50	2.41
165	52.10	50	2.10
170	51.81	49.69	2.12
175	51.54	49.69	1.85
180	51.27	47.76	3.51

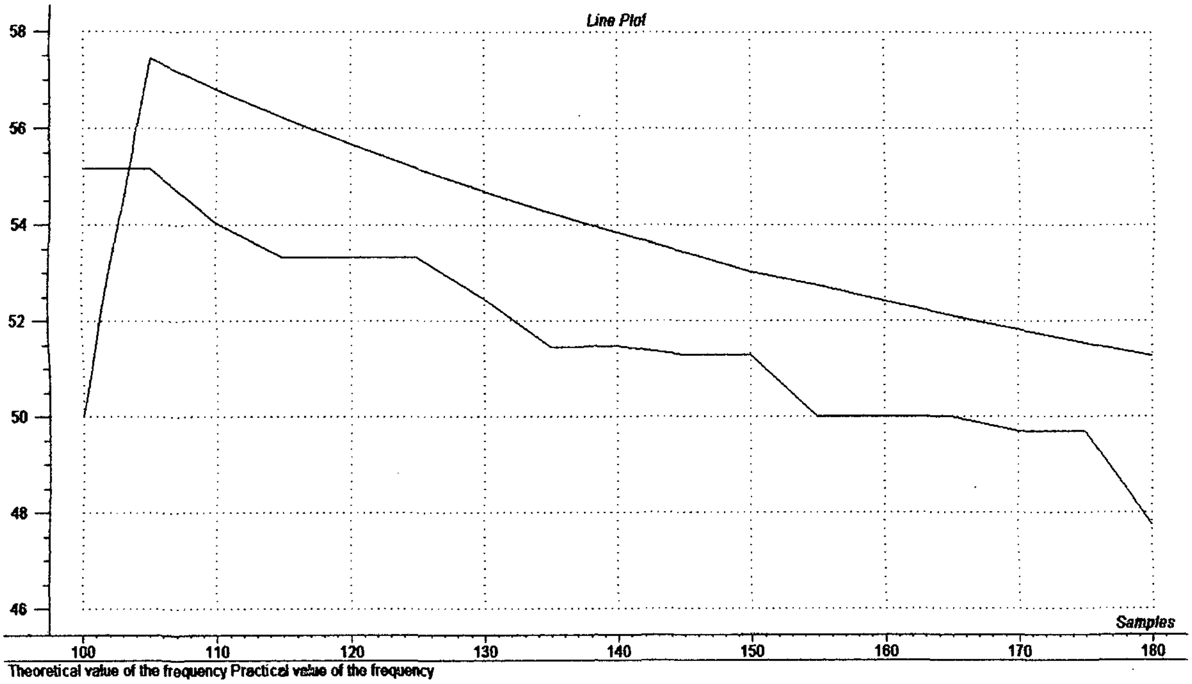
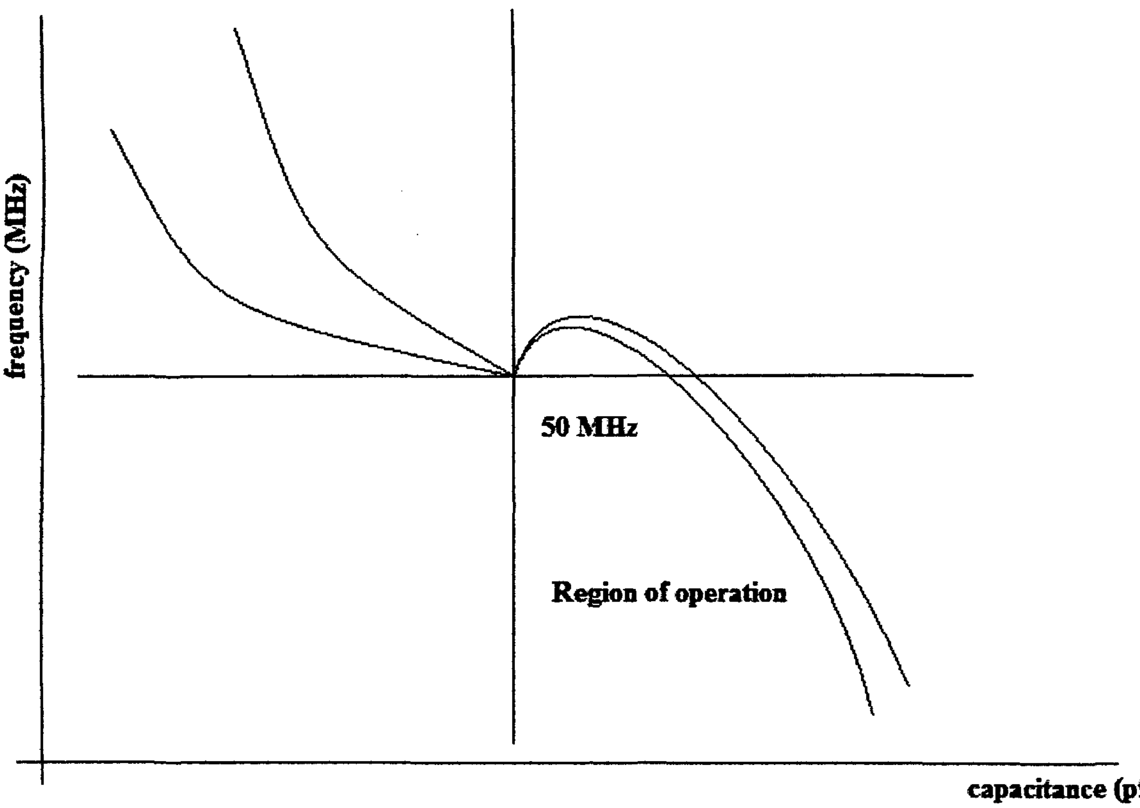


Fig.6.3 Frequency vs capacitance for frequencies near to 50 MHz for transistor MMBT 2369lt1

The values of the frequency of oscillation obtained theoretically and practically are not much different with an average error of 2.34 MHz. Thus the oscillator is implemented for frequencies near to 50 MHz.



CONCLUSION:-

The oscillator design is used for frequencies near to 50MHz because the output of the oscillator is stable and accurate at frequencies near to 50MHz. The capacitance of the capacitive sensor increases with increase in the soil moisture content so the oscillator always works in the region of frequencies near to 50MHz.

The oscillator design is used for the frequencies near to 50MHz because of the following advantages:-

1. The output of the oscillator is stable and accurate at frequencies near to 50MHz.
2. The frequencies in the range of 10 kHz to 25 MHz, 25MHz to 300MHz and 300MHz to 3GHz are said to be high frequencies, very high frequencies and ultra high frequencies. The distortion in the signal due to enviromental noise and soil medium is higher for ultra high frequencies as compared to very high frequencies. Since the frequencies near to 50MHz are in the range of very high frequencies therefore the distortion in the signal due to enviromental noise and soil medium is low for these frequencies as compared to frequencies near to 1.024GHz which are in the range of ultra high frequencies.

6.4 SIMULATION RESULTS OBTAINED FOR THE COLPITTS OSCILLATOR:-

The capacitor C1 of the oscillator is divided into two parallel capacitors C3 and C4 having capacitances 100 pF and 0.66 pF. The capacitor C4 forms the part of the capacitive probe sensor. Thus the frequency of oscillation is given by

$$f = \frac{1}{2\pi * \mathrm{sqrt}(L*((C3+C4)*C2)/((C3+C4)+C2))}$$

L = 0.15µH

C3 = 100pF

C4 = 0.66pF

C2 = 100pF

VARIATION IN THE FREQUENCY OF OSCILLATION THEORETICALLY AND PRACTICALLY THROUGH SIMULATION:-

Frequency (MHz) / Capacitance (pF)	Theoretical value of the frequency	Practical value of the frequency	Error in the frequency
0.66	58.05	54.79	3.26
10	56.8	54.05	2.03
15	56.22	53.33	2.89
20	55.67	53.33	2.34
25	55.16	53.33	1.83
30	54.69	52.46	2.23
35	54.25	51.46	2.79
40	53.83	51.48	2.35
45	53.44	51.28	2.16
50	53.03	51.28	1.75
53.11	52.86	50.96	1.90

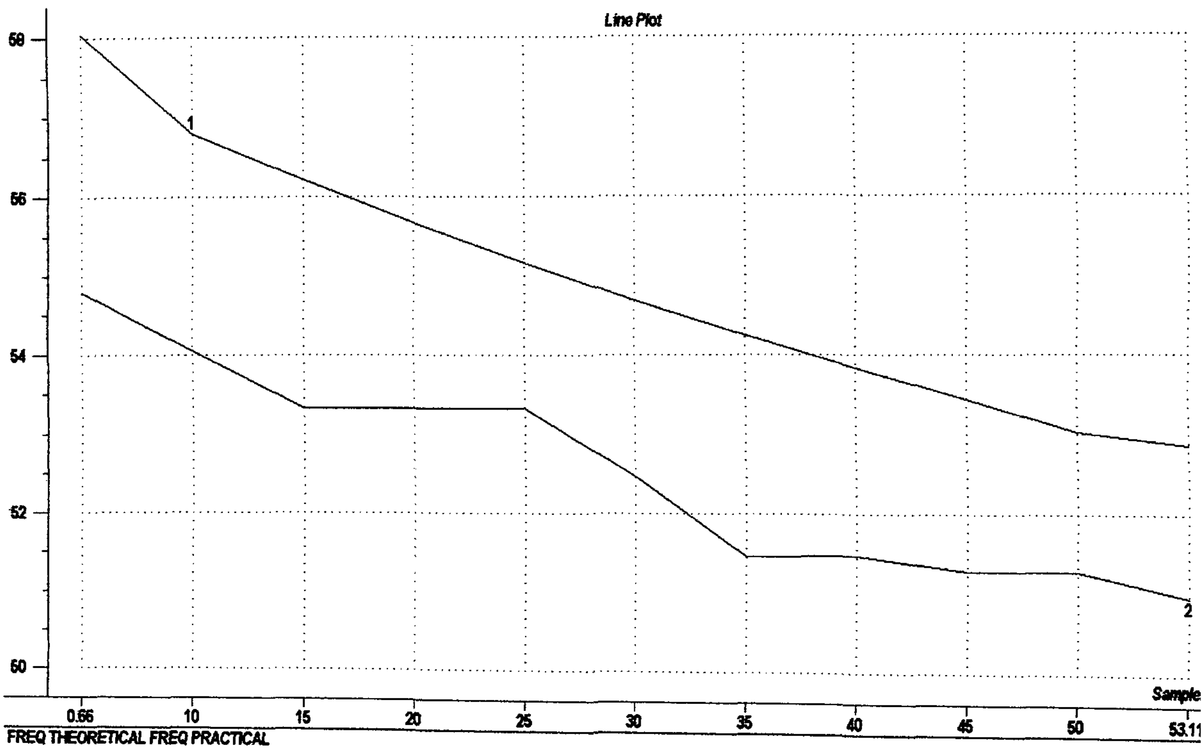


Fig.6.5 Frequency vs capacitance

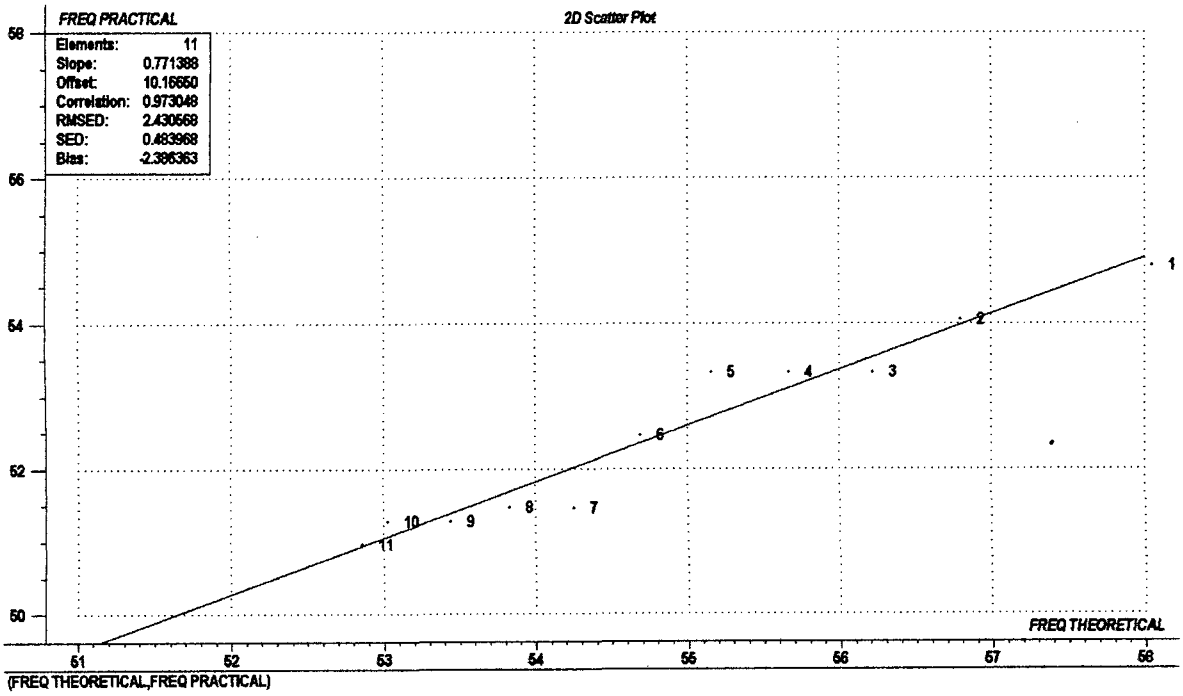


Fig.6.6 Correlation between the theoretical values and the practical values of the frequency

A linearized graph is drawn between theoretical and practical values of the frequency showing the correlation between the theoretical and practical values of the frequency. The correlation coefficient is 0.973048 which is very close to 1. The root mean square error of deviation is 2.430568MHz which is very low. The standard error of deviation is 0.483968MHz which close to 0. Thus the practical values are very close to the theoretical values of the frequency.

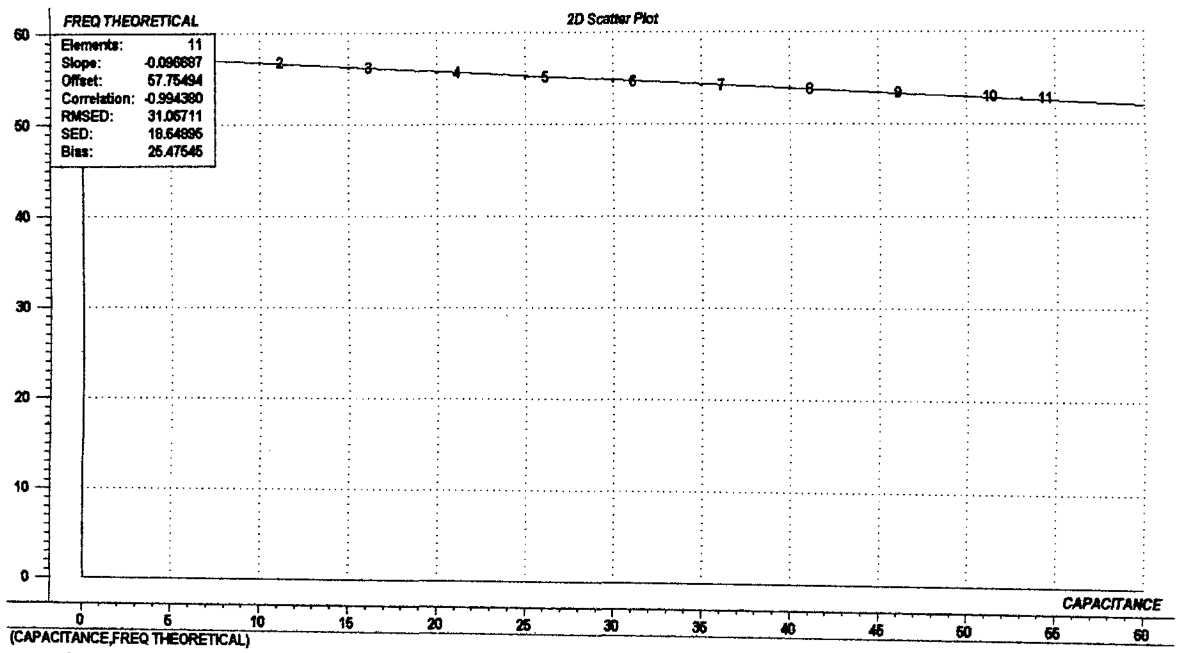


Fig.6.7 Theoretical frequency vs capacitance

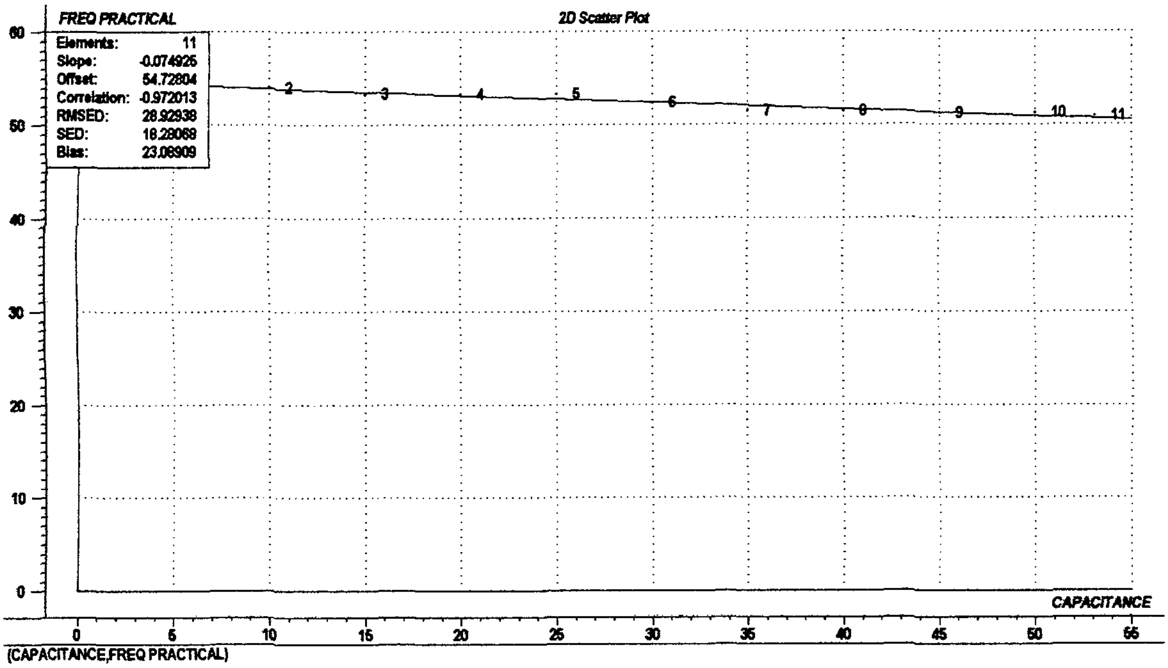


Fig.6.8 Practical frequency vs capacitance

A linearized graph is drawn between practical values of the frequency and capacitance showing the correlation between the practical values of the frequency and capacitance. The correlation coefficient is *-0.972013* which is very close to *1*.

The Colpitts oscillator is simulated for the proposed capacitive probe sensor with following specifications:-

1. Resolution - 0.66pF
2. Sensitivity – 0.17pF
3. Maximum capacitance – 53.1pF

VARIATION IN THE FREQUENCY OF OSCILLATION THEORETICALLY AND PRACTICALLY THROUGH SIMULATION:-

Frequency (MHz) / Capacitance(pF)	Theoretical value of the frequency	Practical value of the frequency	Error in the frequency	% Error in the frequency
0.66	58.04926	54.79	3.259257	5.614641
0.83	58.02486	54.47	3.554865	6.126451
1	58.00054	53.82	4.180544	7.207767
1.17	57.9763	54.47	3.506295	6.047808
1.34	57.95212	54.14	3.812117	6.578047
1.51	57.92801	53.82	4.108011	7.091579
1.68	57.90397	54.14	3.763974	6.500373

1.85	57.88001	54.14	3.740009	6.461659
2.02	57.85611	53.82	4.036113	6.976121
2.19	57.83229	54.14	3.692287	6.384473
2.36	57.80853	54.14	3.66853	6.346001
2.53	57.78484	54.47	3.314842	5.736525
2.7	57.76122	53.82	3.941223	6.823302
2.87	57.73767	53.5	4.237672	7.339527
3.04	57.71419	53.5	4.21419	7.301826
3.21	57.69078	54.14	3.550775	6.154841
3.38	57.66743	53.82	3.847428	6.671753
3.55	57.64415	53.82	3.824149	6.634062
3.72	57.62094	54.14	3.480936	6.041095
3.89	57.59779	53.5	4.09779	7.114491
4.06	57.57471	53.82	3.75471	6.521457
4.23	57.5517	53.5	4.051696	7.040098
4.4	57.52875	53.16	4.368748	7.594026
4.57	57.50587	53.5	4.005866	6.966012
4.74	57.48305	53.82	3.663048	6.372398
4.91	57.4603	53.5	3.960296	6.892231
5.08	57.43761	53.82	3.617608	6.298327
5.25	57.41499	53.16	4.254985	7.410931
5.42	57.39243	53.5	3.892426	6.782125
5.59	57.36993	53.5	3.869931	6.745573
5.76	57.3475	53.16	4.187499	7.301973
5.93	57.32513	53.82	3.50513	6.114474
6.1	57.30282	53.82	3.482825	6.077928
6.27	57.28058	53.5	3.780582	6.600111
6.44	57.2584	53.5	3.758401	6.56393
6.61	57.23628	53.5	3.736283	6.527823
6.78	57.21423	53.82	3.394227	5.932488
6.95	57.19223	53.16	4.032232	7.050315
7.12	57.1703	53.82	3.350299	5.860209
7.29	57.14843	53.16	3.988427	6.979067
7.46	57.12662	53.5	3.626616	6.348382
7.63	57.10486	53.5	3.604865	6.312711
7.8	57.08317	53.16	3.923175	6.872734
7.97	57.06154	53.5	3.561544	6.241584
8.14	57.03997	53.16	3.879974	6.802202
8.31	57.01846	53.82	3.198463	5.609522
8.48	56.99701	52.85	4.147012	7.275841
8.65	56.97562	53.5	3.475619	6.100187
8.82	56.95429	53.16	3.794286	6.661985
8.99	56.93301	53.16	3.773011	6.627106
9.16	56.91179	52.85	4.061795	7.137
9.33	56.89064	53.16	3.730636	6.557557
9.5	56.86954	53.16	3.709535	6.522887
9.67	56.84849	53.16	3.688492	6.488286
9.84	56.82751	53.16	3.667507	6.453753

10.01	56.80658	53.16	3.646578	6.419289
10.18	56.78571	53.16	3.625707	6.384894
10.35	56.76489	53.5	3.264892	5.751604
10.52	56.74413	53.5	3.244134	5.717126
10.69	56.72343	52.85	3.873431	6.828627
10.86	56.70279	53.16	3.542785	6.247991
11.03	56.68219	52.85	3.832195	6.760844
11.2	56.66166	53.16	3.50166	6.179945
11.37	56.64118	52.85	3.79118	6.693328
11.54	56.62076	52.85	3.770755	6.659669
11.71	56.60039	52.85	3.750385	6.626077
11.88	56.58007	53.16	3.42007	6.044655
12.05	56.55981	53.16	3.399809	6.010998
12.22	56.5396	53.16	3.379602	5.977407
12.39	56.51945	52.85	3.66945	6.492366
12.56	56.49935	52.85	3.64935	6.459102
12.73	56.4793	53.16	3.319305	5.877029
12.9	56.45931	53.16	3.299313	5.8437
13.07	56.43937	52.85	3.589373	6.359697
13.24	56.41949	52.85	3.569487	6.326692
13.41	56.39965	52.85	3.549653	6.29375
13.58	56.37987	52.85	3.529872	6.260873
13.75	56.36014	52.85	3.510143	6.228059
13.92	56.34047	52.85	3.490466	6.195309
14.09	56.32084	52.55	3.770841	6.695285
14.26	56.30127	52.85	3.451267	6.129999
14.43	56.28174	52.85	3.431745	6.097438
14.6	56.26227	52.85	3.412273	6.06494
14.77	56.24285	52.85	3.392853	6.032506
14.94	56.22348	52.85	3.373484	6.000133
15.11	56.20416	52.85	3.354165	5.967823
15.28	56.1849	52.55	3.634897	6.469526
15.45	56.16568	52.85	3.315678	5.903389
15.62	56.14651	52.85	3.29651	5.871264
15.79	56.12739	52.55	3.577391	6.3737
15.96	56.10832	52.55	3.558322	6.34188
16.13	56.0893	52.55	3.539303	6.310121
16.3	56.07033	52.55	3.520332	6.278422
16.47	56.05141	52.55	3.501411	6.246784
16.64	56.03254	52.55	3.482538	6.215207
16.81	56.01371	52.55	3.463714	6.183689
16.98	55.99494	52.55	3.444938	6.152232
17.15	55.97621	52.55	3.426211	6.120834
17.32	55.95753	52.25	3.707531	6.625617
17.49	55.9389	52.25	3.6889	6.594516
17.66	55.92032	52.25	3.670316	6.563475
17.83	55.90178	52.25	3.65178	6.532493
18	55.88329	52.25	3.63329	6.501569

18.17	55.86485	52.25	3.614848	6.470703
18.34	55.84645	52.25	3.596453	6.439896
18.51	55.8281	52.25	3.578105	6.409146
18.68	55.8098	52.25	3.559803	6.378455
18.85	55.79155	52.25	3.541548	6.347821
19.02	55.77334	52.25	3.523338	6.317245
19.19	55.75518	52.25	3.505175	6.286726
19.36	55.73706	51.95	3.787058	6.794506
19.53	55.71899	51.95	3.768986	6.764276
19.7	55.70096	51.95	3.75096	6.734103
19.87	55.68298	51.95	3.732979	6.703986
20.04	55.66504	51.95	3.715043	6.673925
20.21	55.64715	51.95	3.697153	6.64392
20.38	55.62931	51.95	3.679307	6.613972
20.55	55.61151	51.95	3.661505	6.584079
20.72	55.59375	51.95	3.643748	6.554241
20.89	55.57604	51.95	3.626036	6.524459
21.06	55.55837	51.95	3.608367	6.494732
21.23	55.54074	51.95	3.590743	6.465061
21.4	55.52316	52.25	3.273162	5.895129
21.57	55.50563	52.25	3.255625	5.865397
21.74	55.48813	52.25	3.238131	5.835719
21.91	55.47068	52.25	3.220681	5.806096
22.08	55.45327	52.25	3.203274	5.776528
22.25	55.43591	51.95	3.48591	6.28818
22.42	55.41859	51.95	3.468588	6.258889
22.59	55.40131	51.95	3.451309	6.229653
22.76	55.38407	51.95	3.434073	6.20047
22.93	55.36688	51.95	3.416879	6.171341
23.1	55.34973	51.95	3.399727	6.142266
23.27	55.33262	51.95	3.382618	6.113243
23.44	55.31555	51.95	3.36555	6.084274
23.61	55.29852	51.95	3.348523	6.055358
23.78	55.28154	51.95	3.331539	6.026494
23.95	55.2646	51.95	3.314595	5.997683
24.12	55.24769	51.95	3.297693	5.968925
24.29	55.23083	51.95	3.280832	5.940219
24.46	55.21401	51.95	3.264012	5.911565
24.63	55.19723	51.95	3.247233	5.882963
24.8	55.18049	51.95	3.230494	5.854414
24.97	55.1638	51.95	3.213796	5.825916
25.14	55.14714	51.95	3.197138	5.797469
25.31	55.13052	51.95	3.180521	5.769075
25.48	55.11394	51.95	3.163943	5.740731
25.65	55.09741	51.95	3.147406	5.712439
25.82	55.08091	51.95	3.130908	5.684198
25.99	55.06445	51.95	3.114449	5.656007
26.16	55.04803	51.65	3.39803	6.172846

26.33	55.03165	51.65	3.381651	6.14492
26.5	55.01531	51.65	3.36531	6.117043
26.67	54.99901	51.65	3.349009	6.089217
26.84	54.98275	51.65	3.332746	6.06144
27.01	54.96652	51.65	3.316523	6.033714
27.18	54.95034	51.65	3.300337	6.006037
27.35	54.93419	51.65	3.284191	5.978409
27.52	54.91808	51.65	3.268082	5.950831
27.69	54.90201	51.65	3.252012	5.923302
27.86	54.88598	51.65	3.23598	5.895823
28.03	54.86999	51.65	3.219986	5.868392
28.2	54.85403	51.65	3.204029	5.84101
28.37	54.83811	51.65	3.18811	5.813677
28.54	54.82223	51.65	3.172229	5.786392
28.71	54.80639	51.65	3.156385	5.759156
28.88	54.79058	51.65	3.140578	5.731968
29.05	54.77481	51.65	3.124809	5.704828
29.22	54.75908	51.65	3.109076	5.677737
29.39	54.74338	51.65	3.09338	5.650693
29.56	54.72772	51.65	3.077721	5.623697
29.73	54.7121	51.65	3.062099	5.596749
29.9	54.69651	51.65	3.046513	5.569848
30.07	54.68096	51.36	3.320963	6.073344
30.24	54.66545	51.36	3.305449	6.046688
30.41	54.64997	51.36	3.289972	6.020079
30.58	54.63453	51.36	3.27453	5.993517
30.75	54.61912	51.36	3.259124	5.967002
30.92	54.60375	51.36	3.243754	5.940533
31.09	54.58842	51.65	2.93842	5.382863
31.26	54.57312	51.65	2.92312	5.356337
31.43	54.55786	51.65	2.907857	5.329859
31.6	54.54263	51.65	2.892628	5.303426
31.77	54.52743	51.36	3.167434	5.808882
31.94	54.51228	51.36	3.152276	5.78269
32.11	54.49715	51.36	3.137152	5.756543
32.28	54.48206	51.36	3.122063	5.730442
32.45	54.46701	51.36	3.107008	5.704386
32.62	54.45199	51.36	3.091988	5.678375
32.79	54.437	51.36	3.077002	5.652409
32.96	54.42205	51.36	3.062051	5.626489
33.13	54.40713	51.36	3.047133	5.600613
33.3	54.39225	51.36	3.03225	5.574783
33.47	54.3774	51.36	3.0174	5.548996
33.64	54.36258	51.36	3.002584	5.523255
33.81	54.3478	51.36	2.987802	5.497558
33.98	54.33305	51.36	2.973053	5.471905
34.15	54.31834	51.36	2.958338	5.446296
34.32	54.30366	51.36	2.943655	5.420732

34.49	54.28901	51.07	3.219006	5.929389
34.66	54.27439	51.07	3.20439	5.904056
34.83	54.25981	51.07	3.189807	5.878767
35	54.24526	51.07	3.175257	5.853521
35.17	54.23074	51.07	3.16074	5.828318
35.34	54.21625	51.07	3.146255	5.803158
35.51	54.2018	51.07	3.131803	5.778041
35.68	54.18738	51.07	3.117383	5.752968
35.85	54.17299	51.07	3.102995	5.727937
36.02	54.15864	51.07	3.088639	5.702948
36.19	54.14432	51.07	3.074316	5.678003
36.36	54.13002	51.07	3.060024	5.6531
36.53	54.11576	51.07	3.045764	5.628239
36.7	54.10154	51.07	3.031536	5.60342
36.87	54.08734	51.07	3.01734	5.578644
37.04	54.07318	51.07	3.003175	5.553909
37.21	54.05904	51.07	2.989042	5.529217
37.38	54.04494	51.07	2.974939	5.504566
37.55	54.03087	51.07	2.960868	5.479957
37.72	54.01683	51.07	2.946828	5.455389
37.89	54.00282	51.07	2.932819	5.430863
38.06	53.98884	50.79	3.198841	5.925005
38.23	53.97489	50.79	3.184894	5.900695
38.4	53.96098	50.79	3.170977	5.876427
38.57	53.94709	50.79	3.157091	5.852199
38.74	53.93324	50.79	3.143236	5.828012
38.91	53.91941	50.79	3.12941	5.803866
39.08	53.90562	50.79	3.115616	5.779761
39.25	53.89185	50.79	3.101851	5.755695
39.42	53.87812	50.79	3.088116	5.73167
39.59	53.86441	50.79	3.074411	5.707686
39.76	53.85074	50.79	3.060736	5.683741
39.93	53.83709	50.79	3.047091	5.659836
40.1	53.82348	50.79	3.033476	5.635971
40.27	53.80989	50.79	3.01989	5.612146
40.44	53.79633	50.79	3.006333	5.588361
40.61	53.78281	50.79	2.992806	5.564615
40.78	53.76931	50.79	2.979309	5.540909
40.95	53.75584	50.79	2.96584	5.517242
41.12	53.7424	50.79	2.9524	5.493615
41.29	53.72899	50.79	2.93899	5.470026
41.46	53.71561	50.79	2.925608	5.446477
41.63	53.70226	50.79	2.912255	5.422967
41.8	53.68893	50.79	2.898931	5.399495
41.97	53.67564	50.79	2.885636	5.376063
42.14	53.66237	50.79	2.872369	5.352669
42.31	53.64913	50.79	2.85913	5.329313
42.48	53.63592	50.79	2.84592	5.305997

42.65	53.62274	50.79	2.832738	5.282718
42.82	53.60958	50.79	2.819584	5.259478
42.99	53.59646	50.79	2.806459	5.236276
43.16	53.58336	50.79	2.793361	5.213112
43.33	53.57029	50.79	2.780291	5.189986
43.5	53.55725	50.79	2.767249	5.166899
43.67	53.54423	50.79	2.754234	5.143849
43.84	53.53125	50.5	3.031248	5.662576
44.01	53.51829	50.5	3.018288	5.639732
44.18	53.50536	50.5	3.005356	5.616926
44.35	53.49245	50.5	2.992452	5.594157
44.52	53.47957	50.5	2.979575	5.571425
44.69	53.46672	50.5	2.966724	5.548731
44.86	53.4539	50.5	2.953901	5.526073
45.03	53.44111	50.5	2.941105	5.503452
45.2	53.42834	50.5	2.928336	5.480868
45.37	53.41559	50.5	2.915594	5.45832
45.54	53.40288	50.5	2.902879	5.435809
45.71	53.39019	50.5	2.89019	5.413335
45.88	53.37753	50.5	2.877527	5.390897
46.05	53.36489	50.5	2.864891	5.368495
46.22	53.35228	50.5	2.852282	5.346129
46.39	53.3397	50.5	2.839699	5.3238
46.56	53.32714	50.5	2.827142	5.301507
46.73	53.31461	50.5	2.814611	5.279249
46.9	53.30211	50.5	2.802107	5.257028
47.07	53.28963	50.5	2.789628	5.234842
47.24	53.27718	50.5	2.777175	5.212692
47.41	53.26475	50.5	2.764748	5.190578
47.58	53.25235	50.5	2.752347	5.168499
47.75	53.23997	50.5	2.739971	5.146455
47.92	53.22762	50.5	2.727621	5.124447
48.09	53.2153	50.5	2.715297	5.102474
48.26	53.203	50.5	2.702998	5.080537
48.43	53.19072	50.23	2.960724	5.566241
48.6	53.17848	50.23	2.948476	5.544491
48.77	53.16625	50.23	2.936252	5.522775
48.94	53.15405	50.23	2.924054	5.501093
49.11	53.14188	50.23	2.911881	5.479447
49.28	53.12973	50.23	2.899733	5.457834
49.45	53.11761	50.23	2.887609	5.436256
49.62	53.10551	50.23	2.875511	5.414713
49.79	53.09344	50.23	2.863437	5.393203
49.96	53.08139	50.23	2.851388	5.371728
50.13	53.06936	50.23	2.839363	5.350287
50.3	53.05736	50.23	2.827363	5.32888
50.47	53.04539	50.23	2.815387	5.307506
50.64	53.03344	50.23	2.803436	5.286167

50.81	53.02151	50.23	2.791509	5.264861
50.98	53.00961	50.23	2.779606	5.243589
51.15	52.99773	50.23	2.767727	5.22235
51.32	52.98587	50.23	2.755872	5.201145
51.49	52.97404	50.23	2.744041	5.179973
51.66	52.96223	50.23	2.732234	5.158835
51.83	52.95045	50.23	2.720451	5.13773
52	52.93869	50.23	2.708692	5.116658
52.17	52.92696	50.23	2.696956	5.095619
52.34	52.91524	50.23	2.685244	5.074613
52.51	52.90356	49.95	2.953555	5.582905
52.68	52.89189	49.95	2.94189	5.562081
52.85	52.88025	49.95	2.930248	5.54129
53.02	52.86863	49.95	2.91863	5.520532

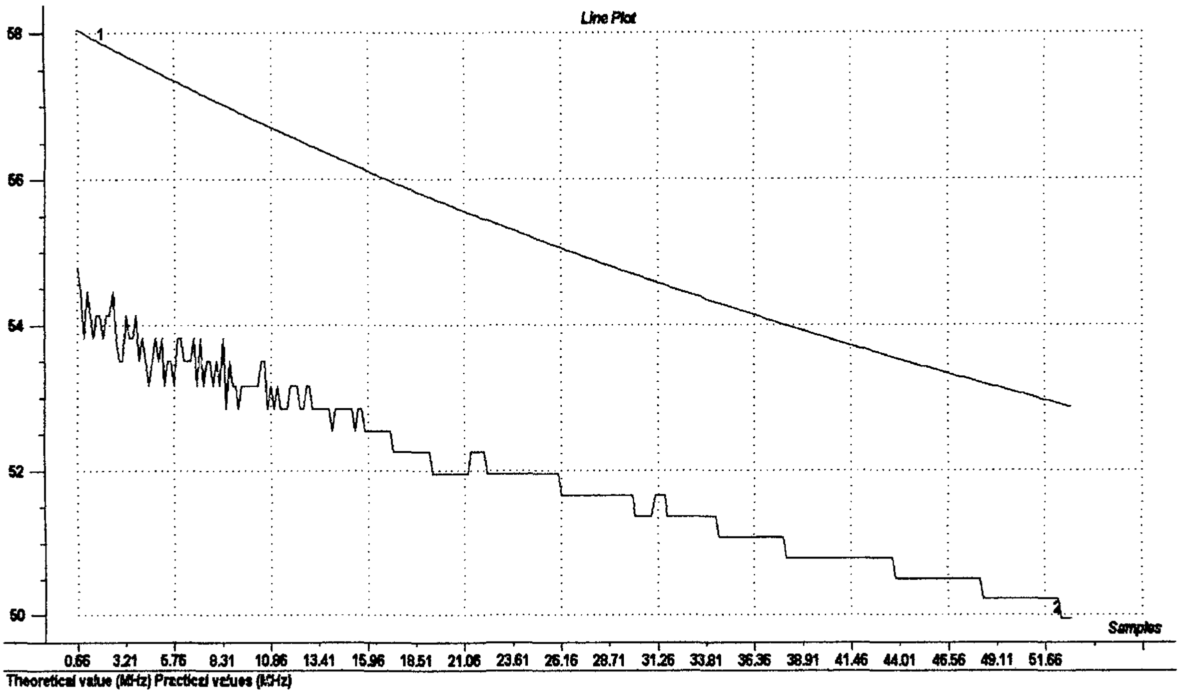


Fig.6.9 Frequency vs capacitance

A linearized graph is drawn between theoretical and practical values of the frequency showing the correlation between the theoretical and practical values of the frequency. The correlation coefficient is 0.990113 which is very close to 1. The root mean square error of deviation is 3.309631MHz which is very low. The standard error of deviation is 0.371166MHz which close to 0. Thus the practical values are very close to the theoretical values of the frequency.

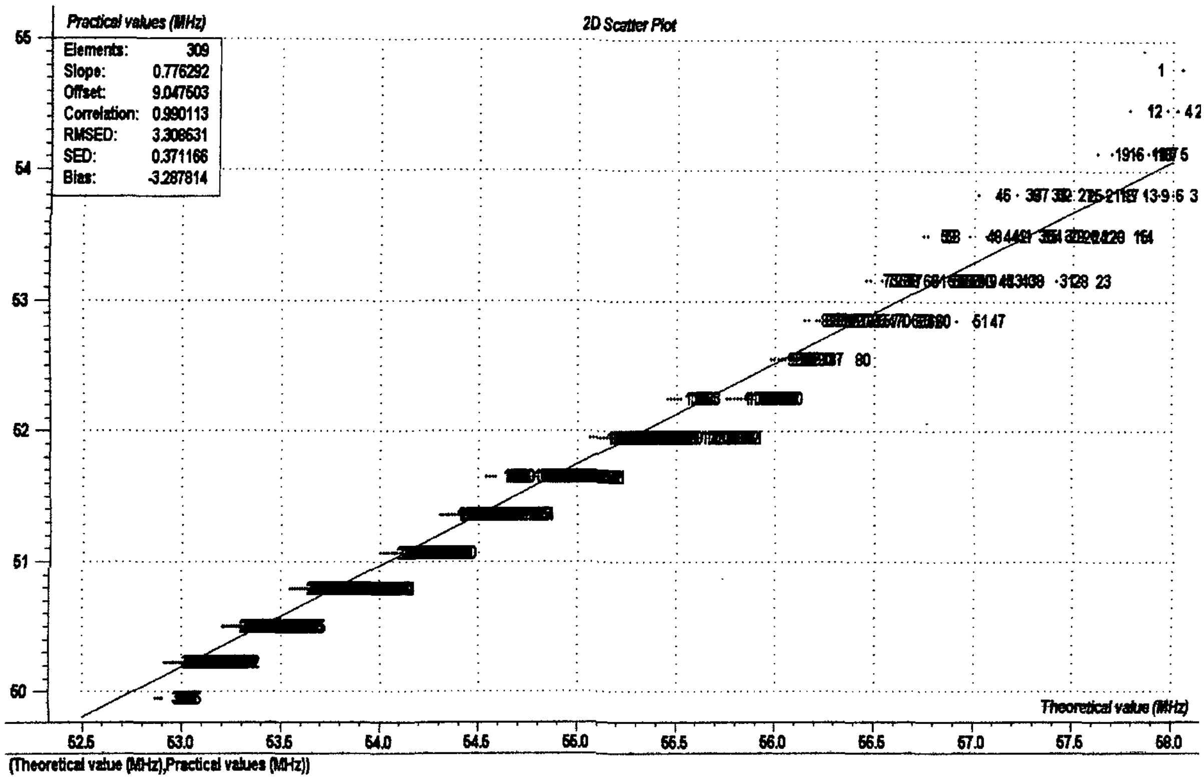


Fig.6.10 Corelation between the theoretical values and the practical values of the frequency

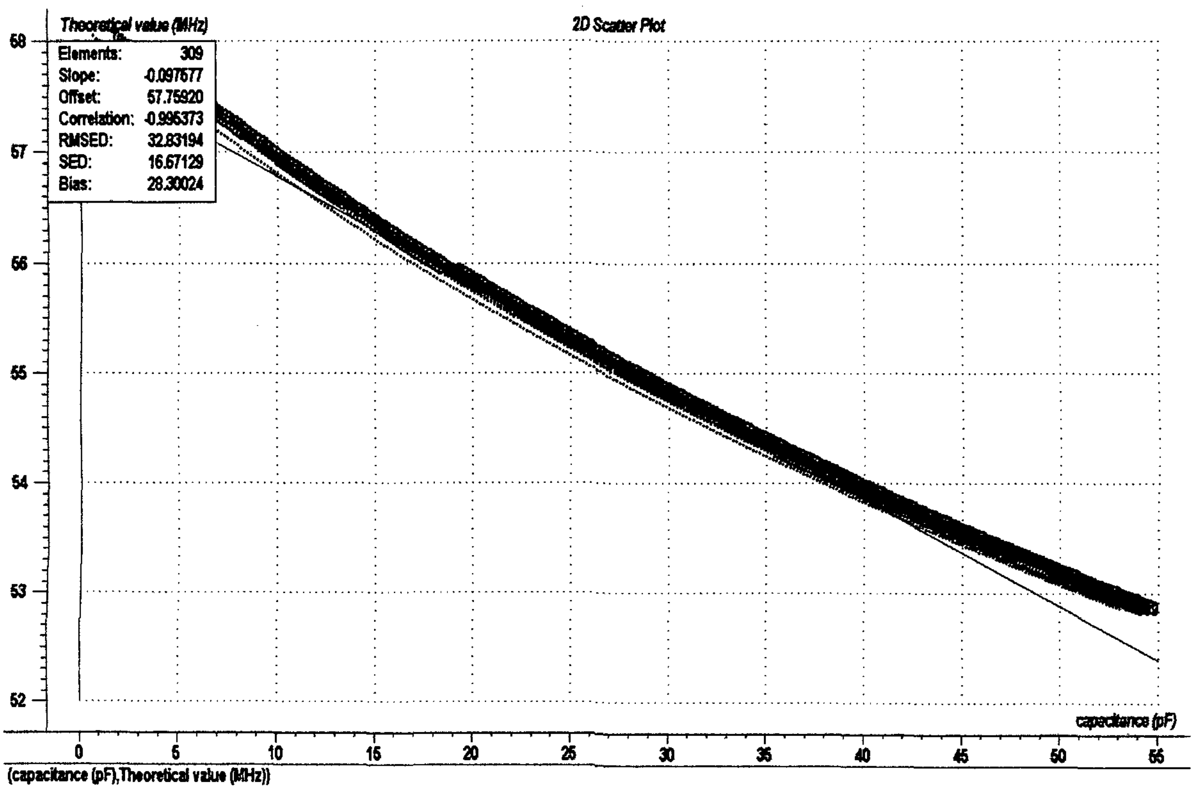


Fig.6.11 Theoretical frequency vs capacitance

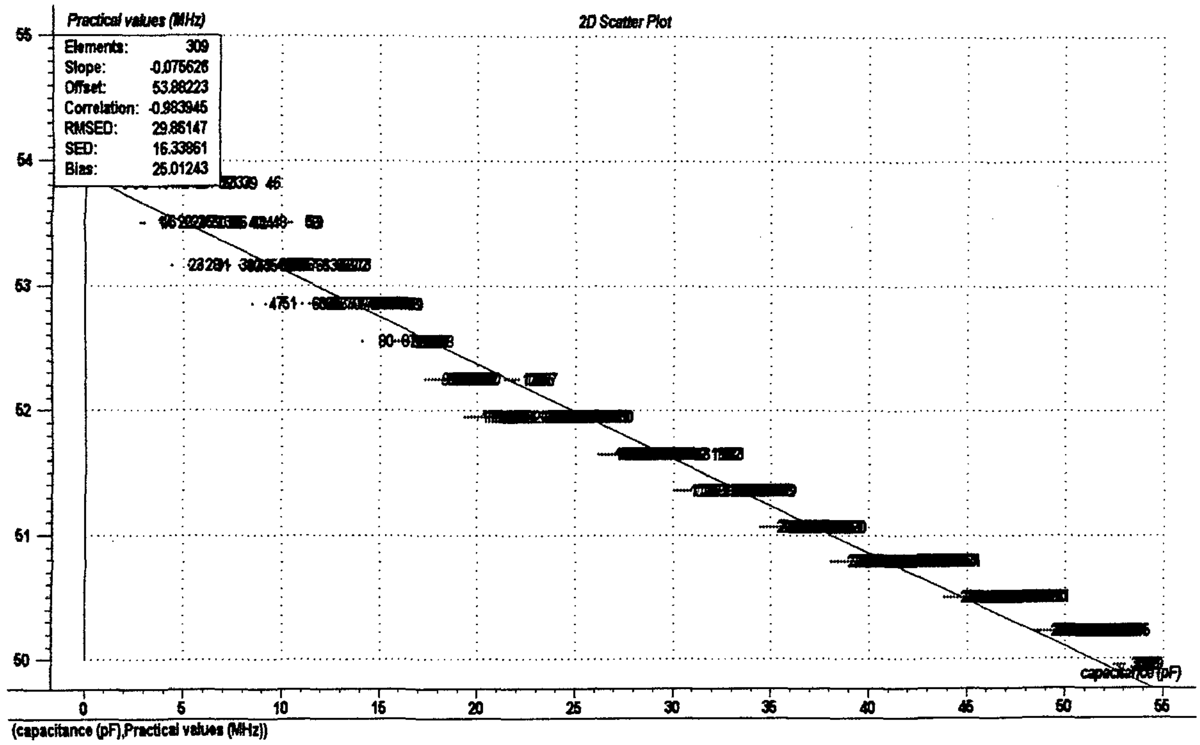


Fig. Practical frequency vs capacitance

A linearized graph is drawn between theoretical and practical values of the frequency showing the correlation between the theoretical and practical values of the frequency. The correlation coefficient is 0.983945 which is very close to 1.

CALIBRATION AND PREDICTION EQUATION OF THE OSCILLATOR:-

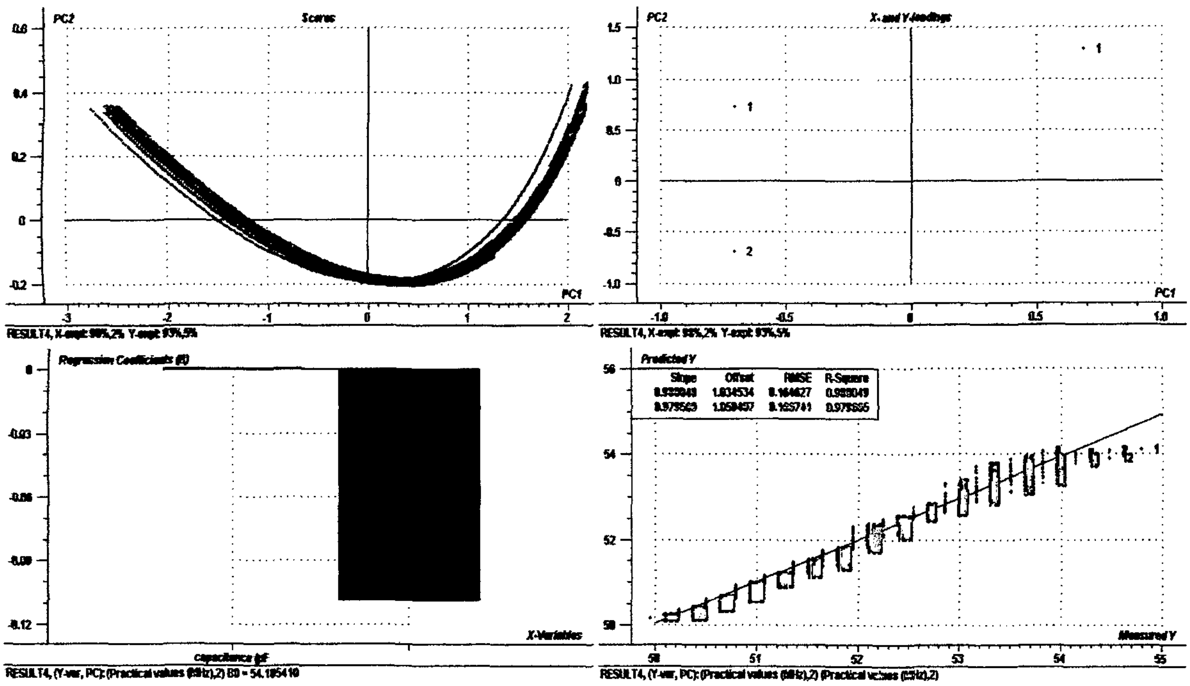


Fig.6.12 Regression between the practical value of the frequency and capacitance

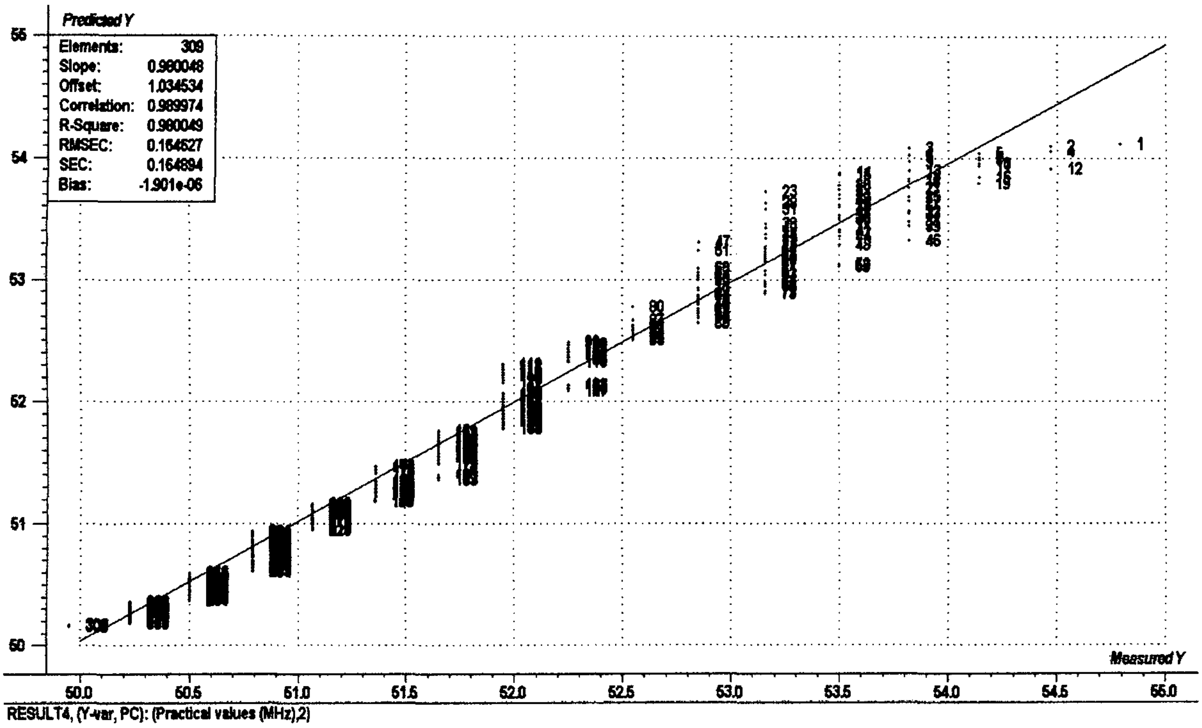


Fig.6.13 Regression between the practical value and theoretical value of the frequency

The regression coefficients for the best fitted polynomial curve between the practical frequency and capacitance of the probe sensor are obtained as:-

$6.182*10^{-4}$, -0.109, 58.185410

Thus the prediction equation for the oscillator is

$$f = 6.182*10^{-4}*C^{2}-0.109*C+58.185410$$

The practical values of the frequency do not vary with capacitance variation in certain intervals of capacitances. Thus for certain capacitance changes the practical values of the frequency do not change. Thus the average sensitivity of the oscillator is equal to 0.105102MHz/pF. The Colpitts oscillator is again simulated for the average sensitivity of 0.105102MHz/pF.

VARIATION IN THE FREQUENCY OF OSCILLATION THEORETICALLY AND PRACTICALLY THROUGH SIMULATION:-

Frequency (MHz) / Capacitance(pF)	Theoretical value of the frequency	Practical value of the frequency	Error in the frequency	% Error in the frequency
0.66	58.04926	54.79	3.259257	5.614641
0.97	58.00483	54.79	3.214831	5.54235

1.28	57.96064	54.79	3.170643	5.470337
1.59	57.91669	54.79	3.126691	5.3986
1.91	57.87157	54.79	3.081567	5.324837
2.22	57.82809	54.79	3.038089	5.253656
2.53	57.78484	54.47	3.314842	5.736525
2.9	57.73352	54.47	3.263523	5.652736
3.27	57.68253	54.47	3.212528	5.569325
3.63	57.63322	54.47	3.163217	5.48853
4	57.58285	54.47	3.112848	5.40586
4.37	57.53279	54.47	3.062793	5.32356
4.74	57.48305	53.82	3.663048	6.372398
5.22	57.41897	53.82	3.598973	6.267916
5.7	57.35541	53.82	3.535409	6.164037
6.18	57.29235	53.82	3.47235	6.060756
6.67	57.22849	53.82	3.408492	5.955935
7.15	57.16643	53.82	3.346435	5.853845
7.63	57.10486	53.5	3.604865	6.312711
8.06	57.05012	53.5	3.550117	6.222805
8.48	56.99701	53.5	3.497012	6.13543
8.91	56.94302	53.5	3.443016	6.046423
9.33	56.89064	53.5	3.390636	5.959919
9.76	56.83738	53.5	3.337375	5.871797
10.18	56.78571	53.16	3.625707	6.384894
10.66	56.72708	53.16	3.567081	6.288144
11.14	56.6689	53.16	3.508901	6.191934
11.62	56.61116	53.16	3.451162	6.096258
12.11	56.55267	53.16	3.392671	5.999135
12.59	56.49581	53.16	3.335809	5.904525
13.07	56.43937	52.85	3.589373	6.359697
13.52	56.38685	52.85	3.536848	6.272469
13.98	56.33353	52.85	3.483533	6.183765
14.43	56.28174	52.85	3.431745	6.097438
14.88	56.23031	52.85	3.380314	6.011551
15.34	56.17811	52.85	3.328108	5.924208
15.79	56.12739	52.55	3.577391	6.3737
16.045	56.09881	52.55	3.548806	6.325993
16.3	56.07033	52.55	3.520332	6.278422
16.56	56.04141	52.55	3.491413	6.230059
16.81	56.01371	52.55	3.463714	6.183689
17.07	55.98502	52.55	3.435018	6.135602
17.32	55.95753	52.25	3.707531	6.625617
17.66	55.92032	52.25	3.670316	6.563475
18	55.88329	52.25	3.63329	6.501569
18.34	55.84645	52.25	3.596453	6.439896
18.68	55.8098	52.25	3.559803	6.378455
19.02	55.77334	52.25	3.523338	6.317245
19.36	55.73706	51.95	3.787058	6.794506
19.7	55.70096	51.95	3.75096	6.734103

20.04	55.66504	51.95	3.715043	6.673925
20.38	55.62931	51.95	3.679307	6.613972
20.72	55.59375	51.95	3.643748	6.554241
21.06	55.55837	51.95	3.608367	6.494732
21.4	55.52316	52.25	3.273162	5.895129
22.19	55.44203	52.25	3.192033	5.757425
22.99	55.36082	52.25	3.110821	5.619174
23.78	55.28154	52.25	3.031539	5.483817
24.57	55.20315	52.25	2.95315	5.349605
25.37	55.12467	52.25	2.874665	5.214844
26.16	55.04803	51.65	3.39803	6.172846
27.17	54.95129	51.65	3.301288	6.007663
28.19	54.85497	51.65	3.204967	5.842619
29.2	54.76093	51.65	3.110925	5.680921
30.21	54.66818	51.65	3.018184	5.520916
31.23	54.57582	51.65	2.925818	5.361015
32.24	54.48561	51.36	3.12561	5.736579
32.62	54.45199	51.36	3.091988	5.678375
32.99	54.41942	51.36	3.059416	5.621919
33.37	54.38613	51.36	3.026131	5.564159
33.74	54.35388	51.36	2.993884	5.508133
34.12	54.32093	51.36	2.960932	5.450812
34.49	54.28901	51.07	3.219006	5.929389
35.09	54.23757	51.07	3.167568	5.840173
35.68	54.18738	51.07	3.117383	5.752968
36.28	54.13675	51.07	3.066746	5.664813
36.87	54.08734	51.07	3.01734	5.578644
37.47	54.03749	51.07	2.967486	5.491532
38.06	53.98884	50.79	3.198841	5.925005
39.02	53.91048	50.79	3.120481	5.788264
39.99	53.83228	50.79	3.042282	5.651409
40.95	53.75584	50.79	2.96584	5.517242
41.91	53.68033	50.79	2.890325	5.384329
42.88	53.60495	50.79	2.814948	5.251285
43.84	53.53125	50.5	3.031248	5.662576
44.61	53.47277	50.5	2.972768	5.559406
45.37	53.41559	50.5	2.915594	5.45832
46.14	53.35821	50.5	2.858213	5.35665
46.9	53.30211	50.5	2.802107	5.257028
47.67	53.24579	50.5	2.745792	5.156824
48.43	53.19072	50.23	2.960724	5.566241
49.11	53.14188	50.23	2.911881	5.479447
49.79	53.09344	50.23	2.863437	5.393203
50.47	53.04539	50.23	2.815387	5.307506
51.15	52.99773	50.23	2.767727	5.22235
51.83	52.95045	50.23	2.720451	5.13773
52.51	52.90356	49.95	2.953555	5.582905

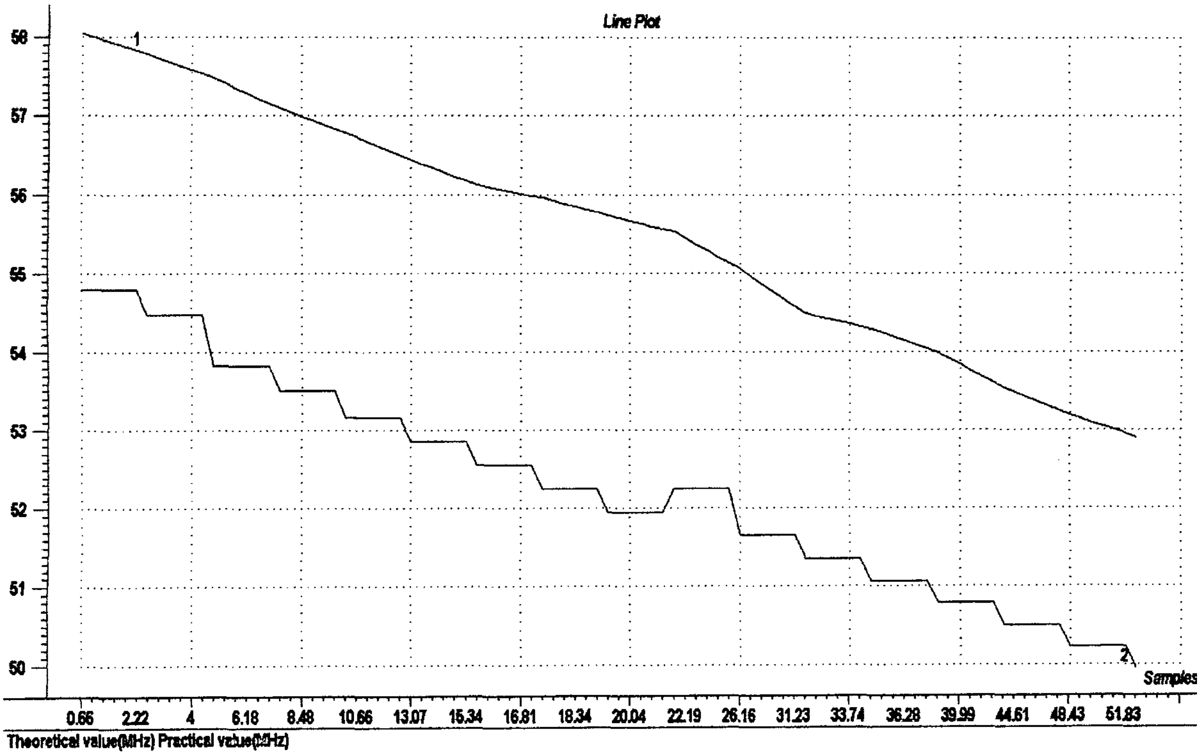


Fig.6.14 Frequency vs capacitance

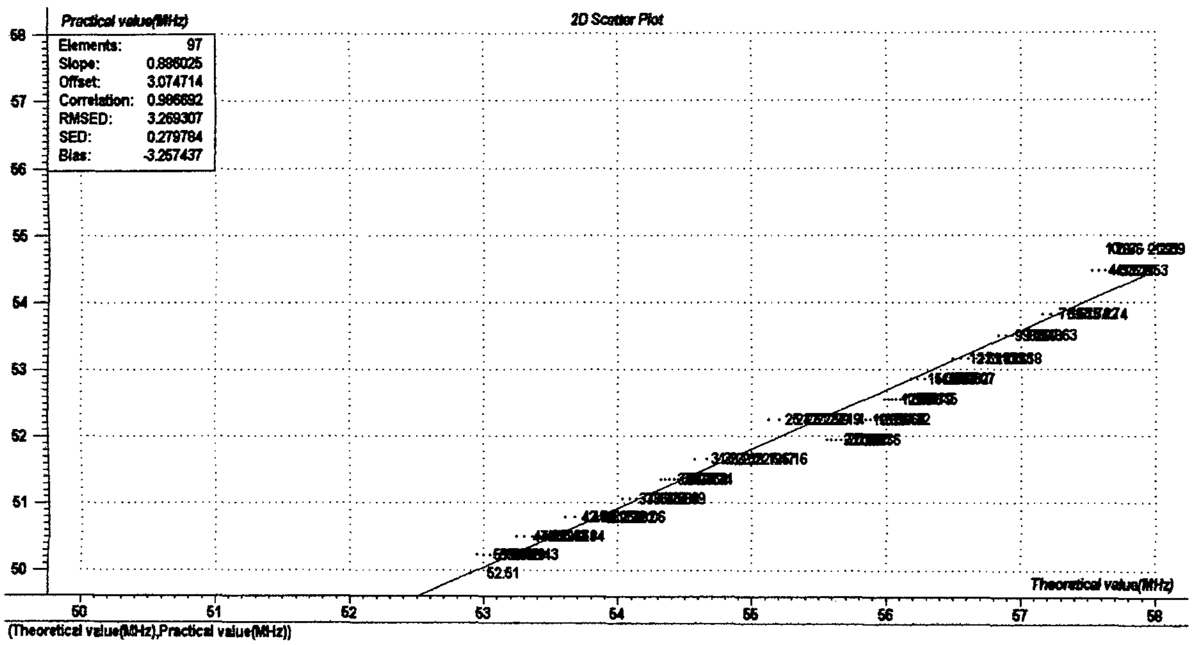


Fig.6.15 Corelation between the theoretical values and the practical values of the frequency

A linearized graph is drawn between theoretical and practical values of the frequency showing the correlation between the theoretical and practical values of the frequency. The correlation coefficient is 0.986692 which is very close to 1. The root mean square error of deviation is 3.269307MHz which is very low. The standard error of deviation is

0.279784MHz which close to 0. Thus the practical values are very close to the theoretical values of the frequency.

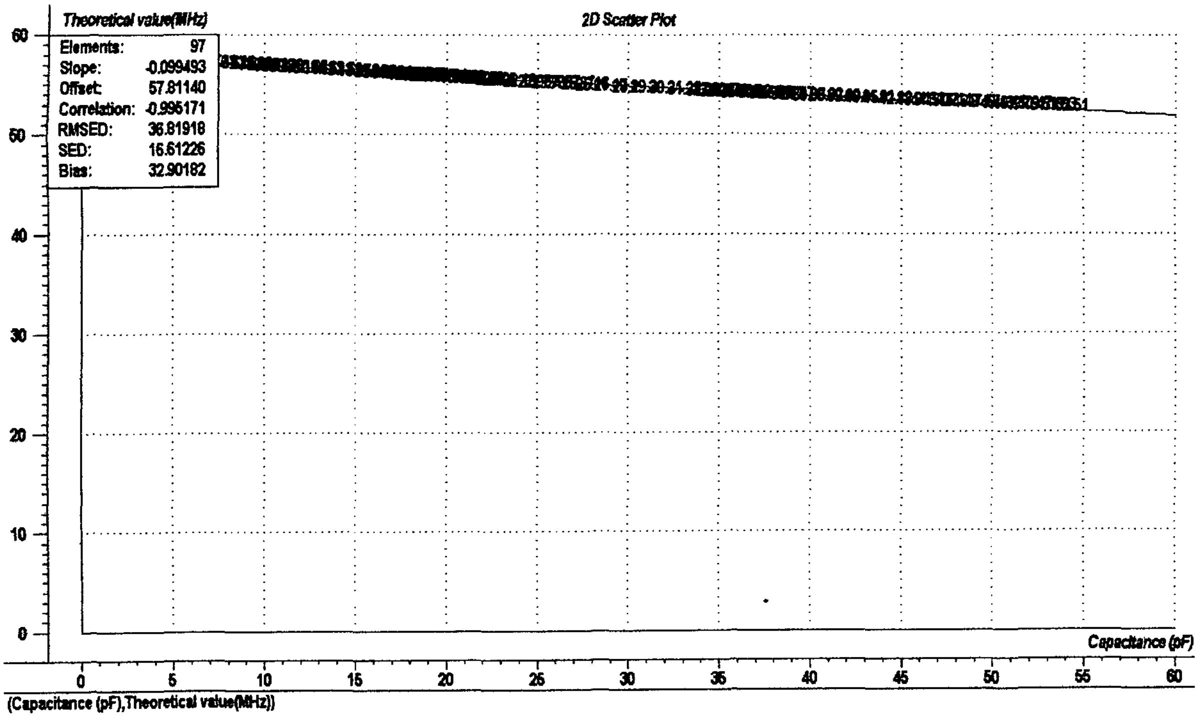


Fig. 6.16 Theoretical frequency vs capacitance

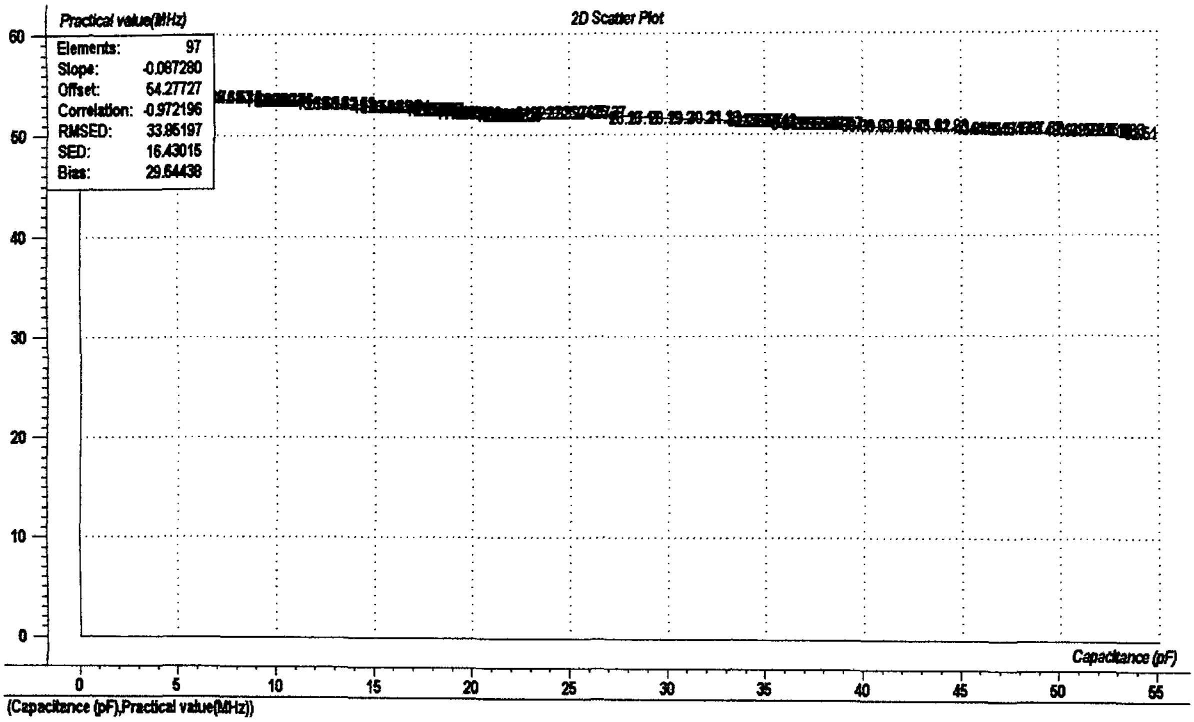


Fig.6.17 Practical frequency vs capacitance

A linearized graph is drawn between theoretical and practical values of the frequency showing the correlation between the theoretical and practical values of the frequency. The correlation coefficient is -0.972196 which is very close to 1.

CALIBRATION AND PREDICTION EQUATION OF THE OSCILLATOR:-

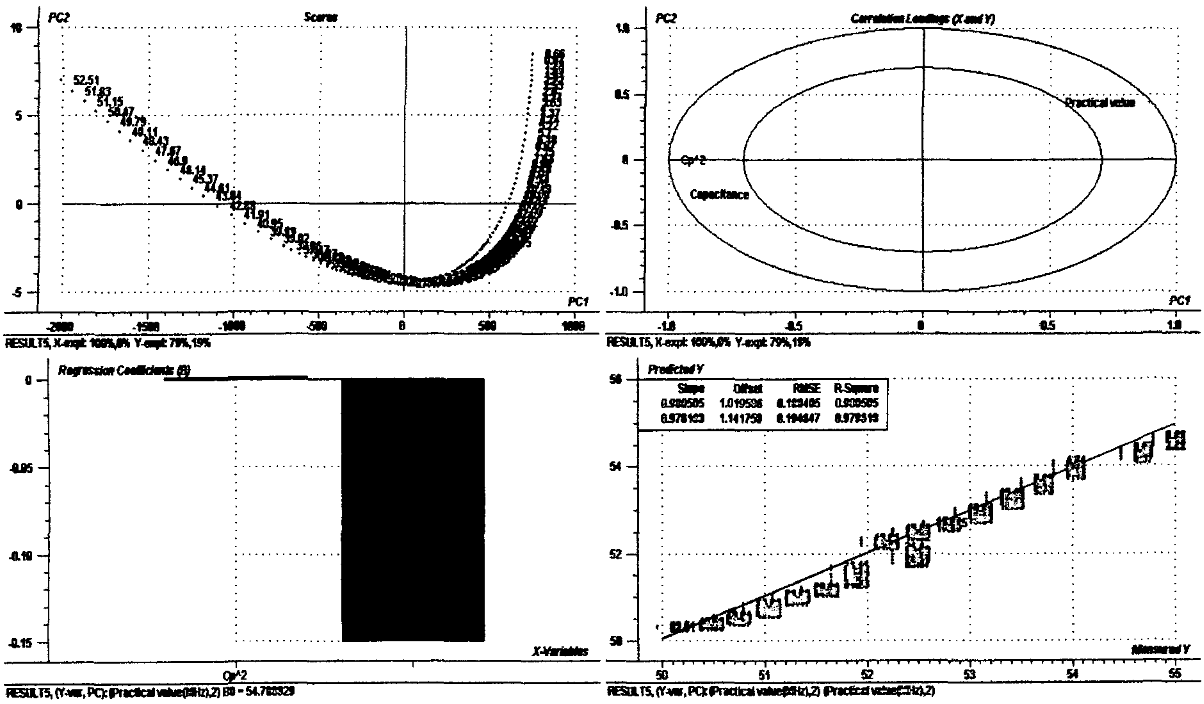


Fig.6.18 Regression between the practical value of the frequency and capacitance

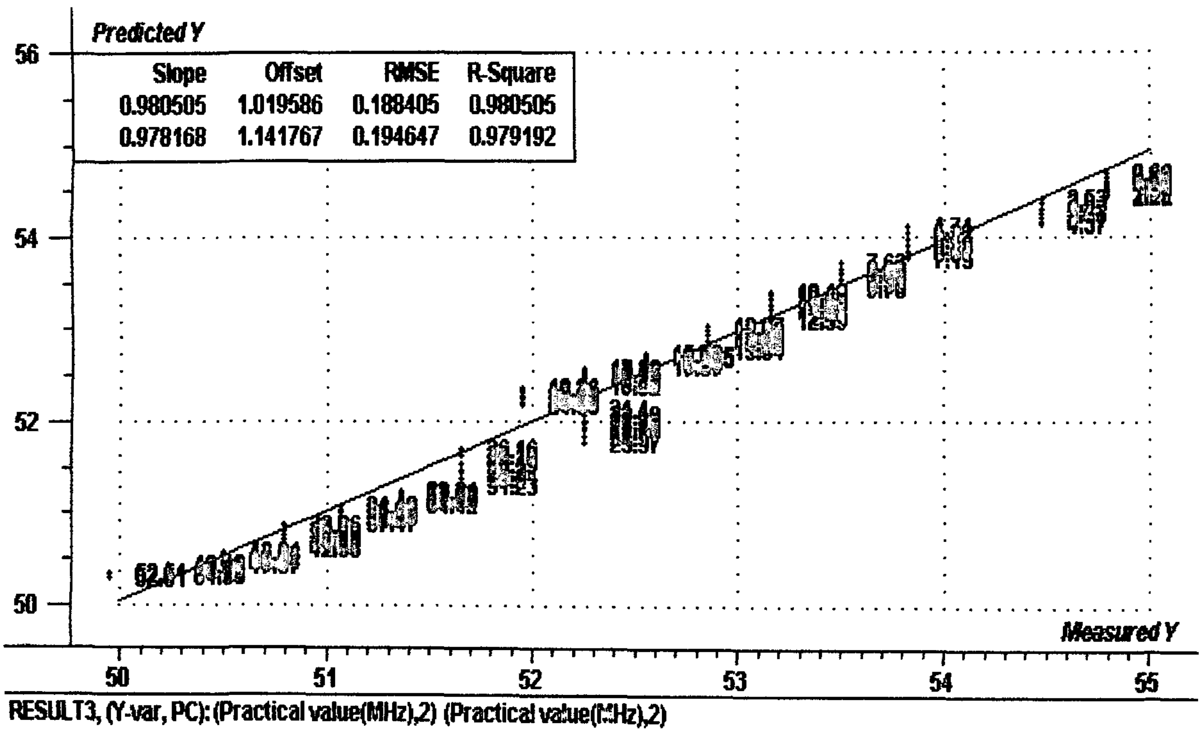


Fig.6.19 Regression between the practical value and theoretical value of the frequency

The regression coefficients for the best fitted polynomial curve between the practical frequency and capacitance of the probe sensor are obtained as:-

$12.28*10^{-4}$, -0.150, 54.788929

Thus the prediction equation for the oscillator is

$$f = 12.28*10^{-4}*C^{2}-0.150*C+54.788929$$

CHAPTER 7
HARDWARE IMPLEMENTATION AND ANALYSIS OF FDR SENSOR SYSTEM

The FDR sensor system is implemented on hardware and experiments are done on soil samples prepared. The experiments are done in order to determine the calibration equation for the FDR sensor system which gives the relationship between the soil moisture and frequency of the oscillator. After the determination of the calibration equation[17][18] the testing of the FDR sensor system can be done on soil samples prepared and the accuracy of the FDR sensor system can be determined after comparison with standard soil moisture sensor.

7.1 CALIBRATION EQUATION OF THE FDR SENSOR SYSTEM:-

The experiments consist of preparation of soil samples, measurement of the capacitance and frequency of the FDR sensor system for the given soil moisture using the Agilent4396B impedance/spectrum analyzer, measurement of the soil moisture of the given samples using POGO soil moisture sensor and interfacing of the impedance/spectrum analyzer and computer for recording and analyzing the data.

A sample of soil is prepared in a container. The soil is kept fine with less number of rocks, organic material and other materials in it. The soil moisture at different regions of the container is kept different in order to do experiments in these different regions. The Agilent4369B impedance/spectrum analyzer is made to operate in impedance mode. An RF frequency sweep of 100kHz to 1.8GHz is applied across the standard capacitance for the calibration of the impedance/spectrum analyzer. The IF bandwidth is kept 10kHz. The capacitance of the connection cables connecting the capacitive probe sensor to impedance/spectrum analyzer is measured for the compensation from the total capacitance measured by the impedance/spectrum analyzer. The capacitive probe sensor is dipped into the soil at certain region of the container and capacitance of the capacitive sensor is measured and recorded on the computer. The soil moisture of that region is then measured by the POGO soil moisture sensor. The measurement of the capacitance is done in various regions of the container. The Agilent4369B impedance/spectrum analyzer is made to operate in spectrum mode. The capacitive sensor is connected to the Colpitts oscillator which is connected to the impedance/spectrum analyzer. The frequency of the oscillator is measured for the same regions of the container. The experiment is again done in the intervals of one hour on order to measure the different moisture of the same region at different times. Thus the soil moisture, capacitance and frequency of the oscillator is measured and recorded on the computer. This data is analyzed to obtain the calibration equation of the FDR sensor system.

7.2 VARIATION OF THE FREQUENCY OF OSCILLATION AND CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE:-

The variation of the frequency of the oscillation of the oscillator and the capacitance of the capacitive probe sensor with the change in the soil moisture is measured in two steps:-

1. Measurement of the variation in the capacitance of the capacitive probe sensor with the change in the soil moisture through impedance mode of the impedance/spectrum analyzer.
2. Measurement of the variation of the frequency of the oscillation of the oscillator with variation in the capacitance of the capacitive probe sensor through the spectrum mode of the impedance/spectrum analyzer.

7.3 VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE:-

The soil samples on which the measurement of the soil moisture is done are prepared into five different ranges of the moisture content:-

1. 0 to 10%
2. 10 to 20%
3. 20 to 30%
4. 30 to 40%
5. 40 to 50%

The soil samples are not prepared for the range above than 50% because the soil samples become very wet and diluted for the range above than 50% making the preparation of the soil samples and measurement of the moisture content in soil samples very difficult.

The soil samples on which the measurement of the soil moisture is done are prepared into different ranges of the soil moisture content because different calibration equations are obtained for different ranges which increases the accuracy of the soil moisture sensor. The calibration equation obtained for a whole range of the soil moisture content from 0 to 50%

may decrease the accuracy of the soil moisture sensor during the regression of the data obtained for the soil moisture sensor in the range of 0 to 50% thus the whole range of the soil moisture content is divided into different ranges.

1. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 0 TO 10%:-

The soil sample for the range of 0 to 10% moisture content is prepared and the measurement of the capacitance of the capacitive probe sensor is done on the soil sample. The moisture content corresponding to the capacitance measured by the impedance/spectrum analyzer at a region of the soil sample is also measured by the POGO soil moisture sensor. The capacitance of the connection cables connecting the capacitive probe sensor to impedance/spectrum analyzer is measured for the compensation from the total capacitance measured by the impedance/spectrum analyzer. The length of the capacitor plates used for the measurement of the capacitance of the capacitive plate sensor are kept equal to the length of the rods of the POGO soil moisture sensor because for the higher length of the capacitor plates as compared to the length of the rods of the POGO soil moisture sensor the volume of the soil content in the soil sample measured by the capacitor plates will be more as compared to the volume measured by POGO soil moisture sensor. The soil moisture content does not remain same throughout the volume of the soil sample but there is variation in the soil moisture content with the height of the volume of the soil at a region in the soil sample. The capacitance of the capacitive probe sensor is proportional to the average dielectric of the soil content between the capacitor plates and thus proportional to the average soil moisture content of the soil content between the capacitor plates. Thus the capacitor plates having more length as compared to the rods of the POGO soil moisture sensor will measure the average soil moisture content of the larger volume of the soil which is different from the average soil moisture content of the volume of the soil measured by the POGO soil moisture sensor. Thus the capacitance of the remaining part of the capacitor plates having air as the dielectric medium is measured for the compensation from the total capacitance measured by the impedance/spectrum analyzer. The capacitance of the remaining part of the capacitive probe sensor inside the plastic electrode holder having delirin material as the dielectric medium is measured for the compensation from the total capacitance measured by the impedance/spectrum analyzer.

The capacitance of the part of the capacitive probe sensor in the soil sample is C1, the capacitance of the remaining part of the capacitive probe sensor in the air is C2, the capacitance of the remaining part of the capacitive probe sensor in the plastic electrode holder is C3, the capacitance of the connection cables is C4 and the total capacitance measured by the impedance/spectrum analyzer is C_{tot}. The capacitance of the capacitive probe sensor is equal to the difference of the total capacitance and sum of the capacitance of the remaining part of the capacitive probe sensor in air, capacitance of the remaining part of the capacitive probe sensor in the plastic electrode holder and the capacitance of the connection cables. Thus

$$C1+C2 = C_{tot} - C3 - C4$$

$$= 81.94246*10^{-12}\text{ F} - 55.17639*10^{-12}\text{ F} - 1.50962122*10^{-12}\text{ F} = 25.25644878*10^{-12}\text{ F}$$

The capacitive probe sensor is dipped in the soil sample upto the length equal to the length of the remaining part of the capacitive probe sensor and the total capacitance of the capacitive probe sensor is measured. Thus

$$(5.8/3.9)*C1 \quad +(3.9/5.8)C2 = C_{tot} - C3 - C4$$

$$= 74.74817*10^{-12}\text{ F} - 55.17639*10^{-12}\text{ F} - 1.50962122*10^{-12}\text{ F} = 18.06215878*10^{-12}\text{ F}$$

The capacitance of the remaining part of the capacitive probe sensor in the air is 1.325 pF.

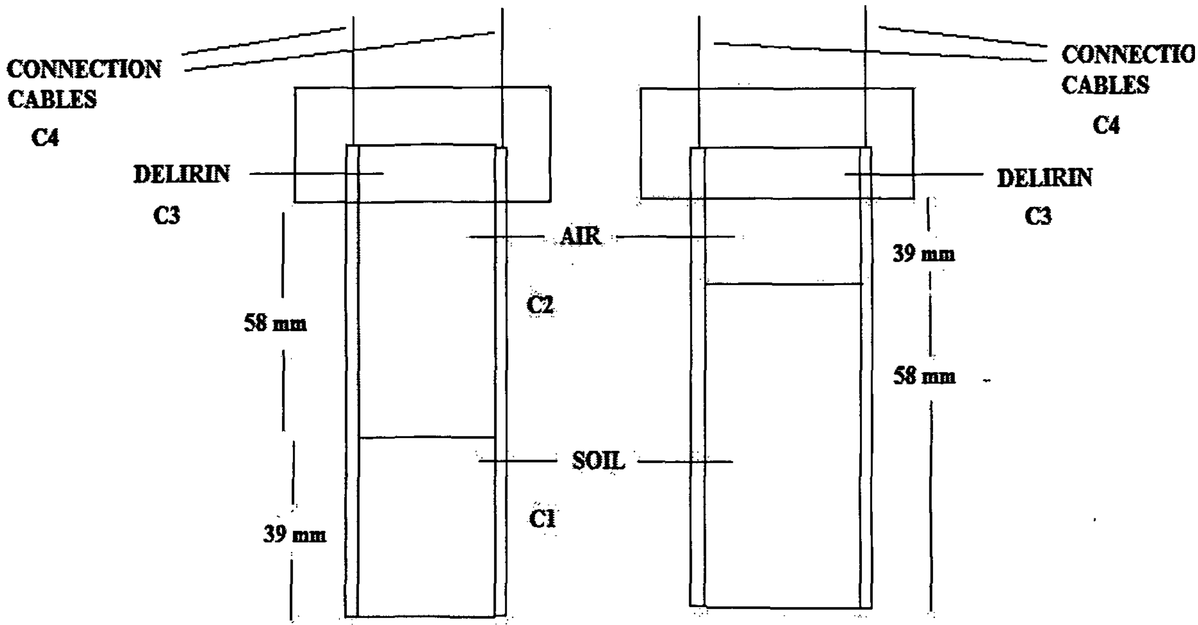


Fig.7.1 Capacitances of the electrodes and the connection cables

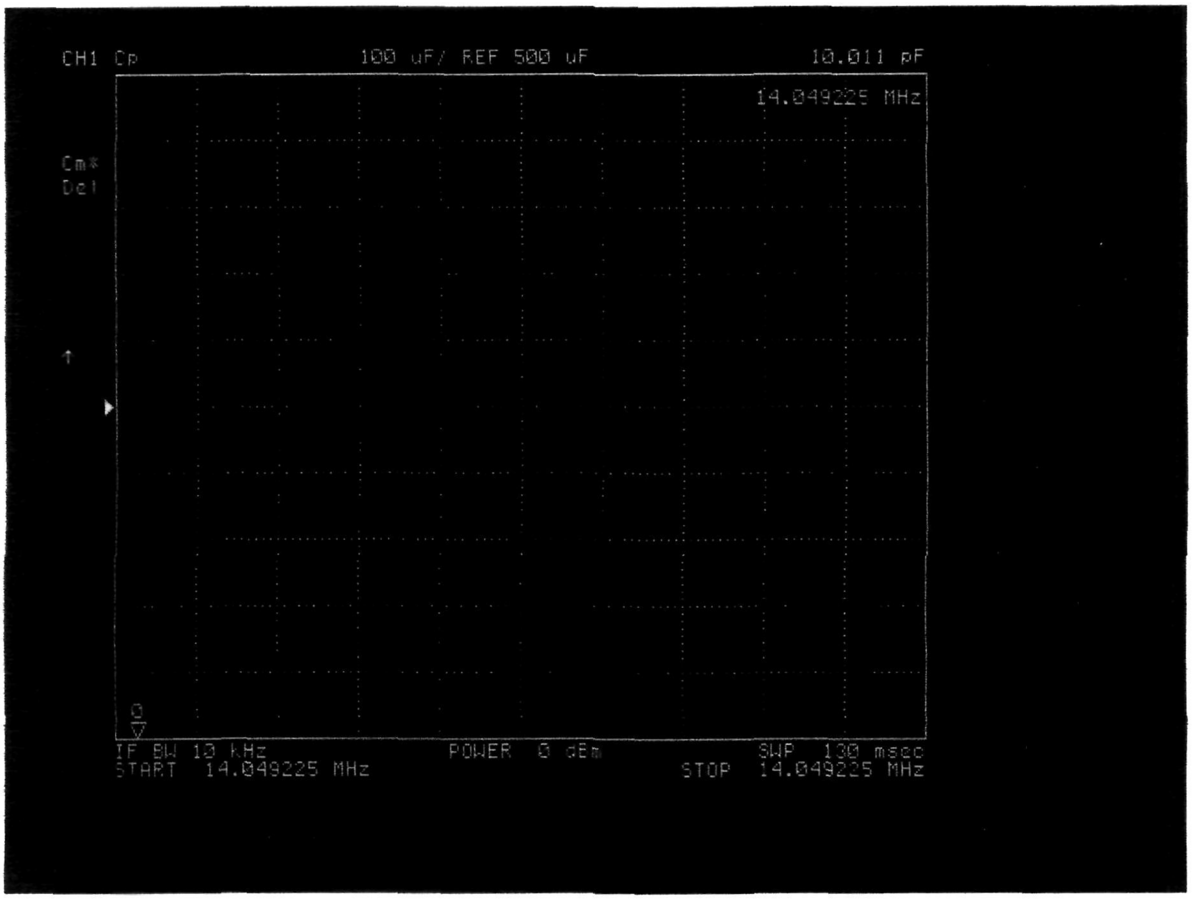


Fig.7.2 Capacitance of the capacitive probe sensor

VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 0 TO 10%:-

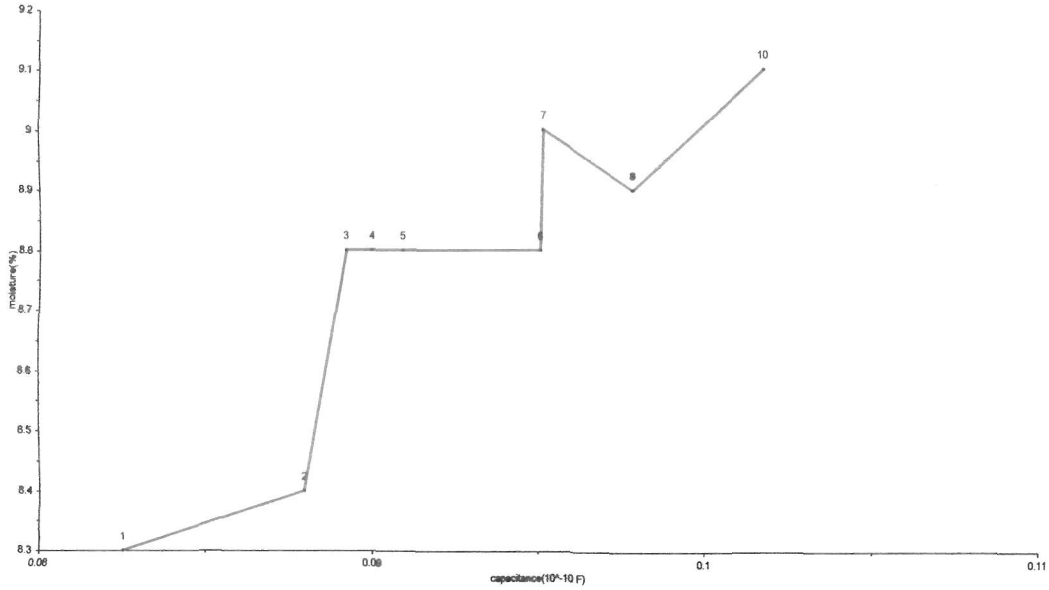


Fig.7.3 Moisture vs capacitance

al tance ıred) F)	Capacitance of the connection cables (10^{-10} F)	Total Capacitance of the electrode inside the plastic electrode holder and in the air (10^{-10} F)	Difference of the capacitances (10^{-10} F)	Actual capacitance of the electrode (10^{-10} F)	Moisture (%)	Calibrated moisture (%)	Error (10^{-2})
'49	0.55176	0.02834	0.77388	0.82530	8.3	8.3881	-8.8081
306	0.55176	0.02834	0.82955	0.87964	8.4	8.5947	-19.469
134	0.55176	0.02834	0.84238	0.89216	8.8	8.6424	15.765
11	0.55176	0.02834	0.85010	0.89970	8.8	8.6711	12.893
508	0.55176	0.02834	0.85976	0.90912	8.8	8.7070	9.3050
)33	0.55176	0.02834	0.90222	0.95056	8.8	8.8649	-6.4948
)42	0.55176	0.02834	0.90316	0.95148	9	8.8685	13.154
15	0.55176	0.02834	0.93049	0.97816	8.9	8.9703	-7.0306
318	0.55176	0.02834	0.93073	0.97839	8.9	8.9712	-7.1185
'20	0.55176	0.02834	0.97093	1.0176	9.1	9.1210	-2.1041

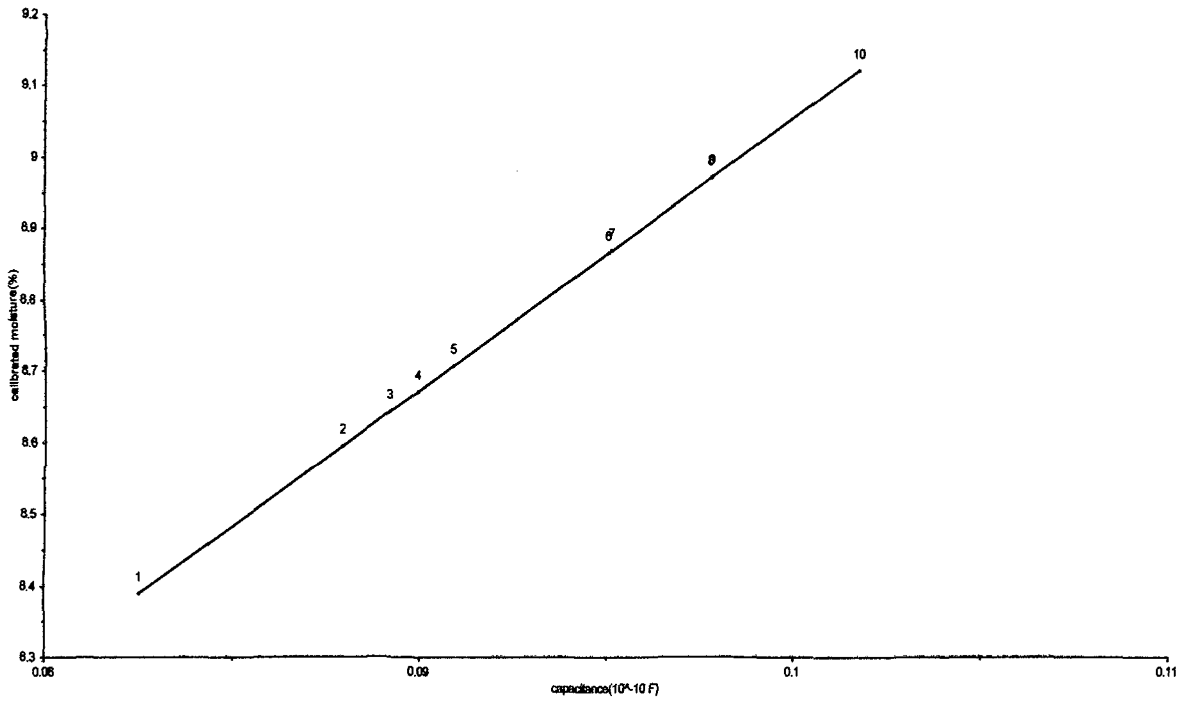


Fig.7.4 Calibrated moisture vs capacitance

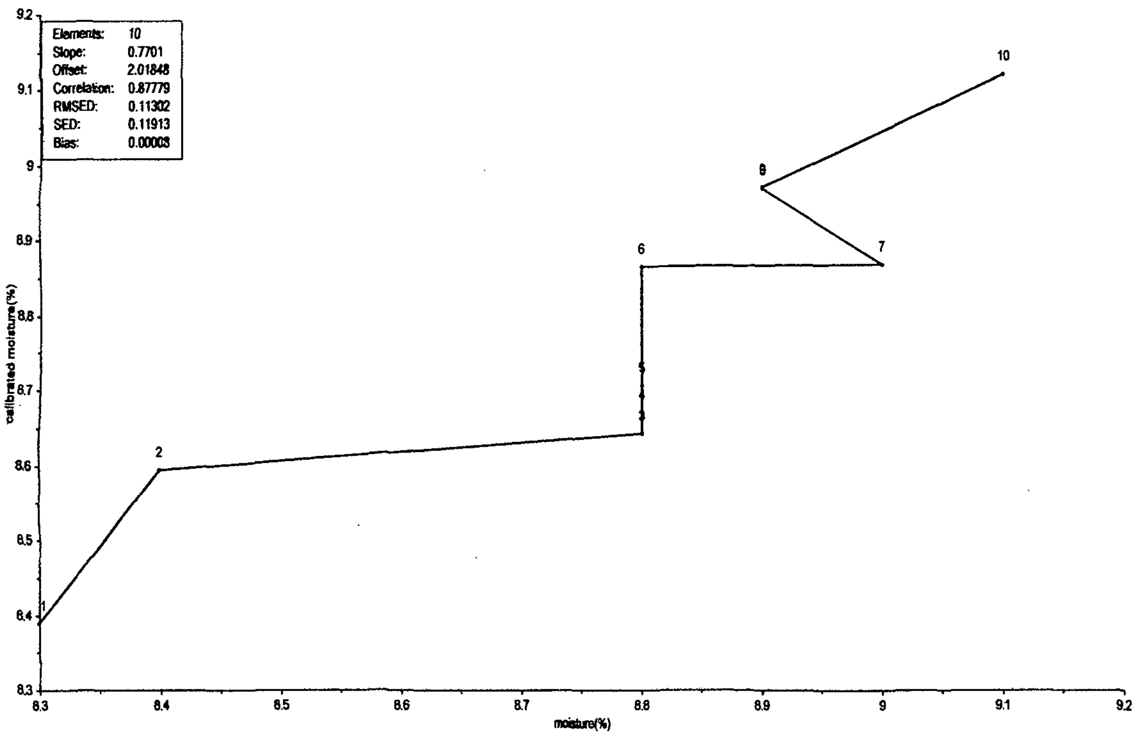


Fig.7.5 Calibrated moisture vs moisture

A graph is drawn between the calibrated moisture and moisture showing the relationship between the calibrated moisture and moisture. The relationship between the calibrated moisture and moisture should be linear with a slope equal to 1 and offset equal to 0. The graph shows that the correlation coefficient is close to 1 equal to 0.87779. The slope is close to 1 equal to 0.7701. The offset is low equal to 2.01848. The root mean square error of deviation RMSED, the squared error of deviation SED and the bias are close to 0 equal to 0.11302, 0.11913 and 0.0008. Thus the relationship between the calibrated moisture and moisture is highly linear.

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the range of 0 to 10% moisture content is obtained by using Partial Least Squares or Projection to Latent Structures regression method. In PLS method the number of original variables is reduced to latent variables or latent structures or principle components or factors. The regression is done between the X-variables or predictors and Y-variables or responses. The number of X-variables capacitance and capacitance square is two thus the number of factors is two factor 1 and factor 2. Thus the regression of X-variables and Y-variables is done for factor 1 and factor 2.

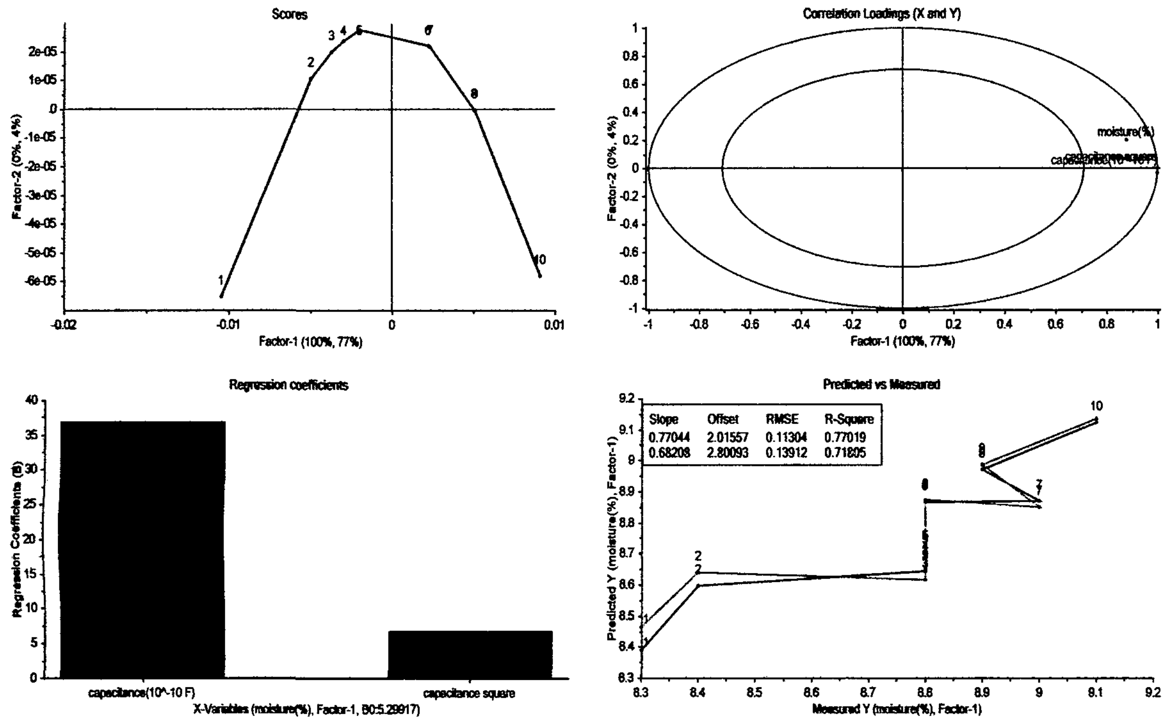


Fig.7.6 Regression between the moisture and capacitance for Factor 1

1. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 1:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot is used to detect the pattern of the samples and the outliers in the samples. An outlier is a sample which is far from groups of samples. The outlier is a sample which do not belong the group or it belongs to the group but samples between the group and the outlier are missing. The outliers which do not belong to the groups of samples do not form the pattern with the group of the samples and reduce the correlation coefficient value and increase the error in the calibration equation and reduce the linearity of the relationship between the calibrated moisture and moisture. The scores plot for factor 1 shows two outliers 1 and 10 in the samples. These outliers belong to the group of the samples because samples are missing between the group of the samples and outliers.

2. LOADINGS PLOT:-

The loadings plot is used to detect the correlation between the X-variables and Y-variables along the factors. The loading plot is used to detect the percentage of the explained variance of X-variables and Y-variables along factors. The variables which are on the same direction from the centre of the plot and close to each other are highly positively correlated and the variables which are on the opposite direction from the centre of the plot are highly negatively correlated. The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The moisture is also on the same direction from the centre of the plot and close to the capacitance and capacitance square. The Y-variable shows 77% explained variance along the factor 1 and 4% explained variance along the factor 2. Thus the moisture is highly positively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot is used to detect regression coefficients of the calibration equation for the factor 1 and factor 2. The higher regression coefficient corresponding to a X-variable shows higher variation of Y-variable with the X-variable and the lower regression coefficient corresponding to a X-variable shows lower variation in Y-variable with the X-variable. The calibration equation with lower regression coefficient corresponding to capacitance square shows a highly linear relationship between capacitance and moisture. The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are 6.758, 36.78, 5.29917.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot is used to detect the correlation coefficient, root mean square error of calibration RMSEC, root mean square error of prediction RMSEP, offset and slope of the regression line corresponding to calibration equation and validation of the calibration equation for the factor 1 and factor 2. The correlation coefficient should be equal to 1. The RMSEC, RMSEP, offset should be equal to 0. The slope should be equal to 1. The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.77019 and 0.71805. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.11304 and 0.13912. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 2.01557 and 2.80093. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.77044 and 0.68208.

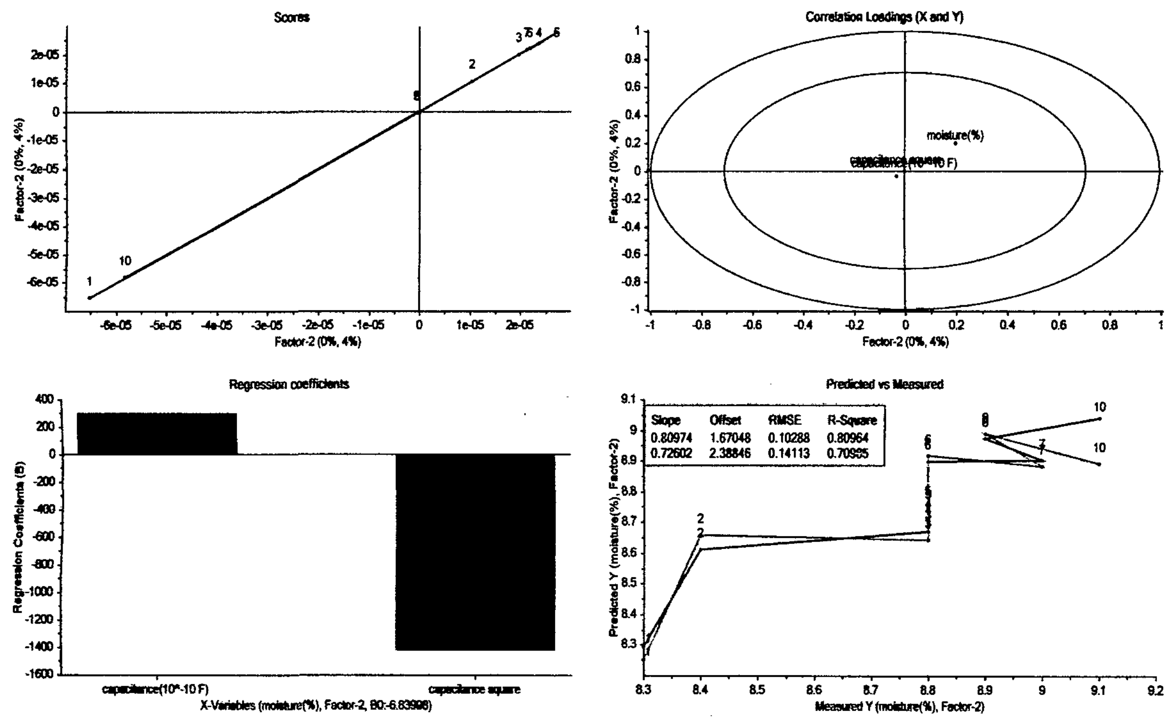


Fig.7.7 Regression between the moisture and capacitance for Factor 2

2. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

5. SCORES PLOT:-

The scores plot for factor 2 shows two outliers 1 and 10 in the samples. These outliers belong to the group of the samples because samples are missing between the group of the samples and outliers.

6. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The moisture and capacitance square are also on the same direction from the centre of the plot. The moisture and capacitance are in opposite direction from the centre of the plot. The moisture is not close to the capacitance and the capacitance square. The Y-variable shows 77% explained variance along the factor 1 and 4% explained variance along the factor 2. Thus the moisture is not highly positively correlated to the capacitance square and not highly negatively correlated to the capacitance for factor 2.

7. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are -1442, 300.7, -6.83998.

8. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.80964 and 0.70985. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.10288 and 0.14113. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 1.67048 and 2.38846. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.80974 and 0.72602.

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation are comparable and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 1 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 0 to 10% moisture content is

$$\theta_v = 6.758*C^2 + 36.78*C + 5.29917$$

θ_v = moisture (%)

C = capacitance (10^{-10} F)

2. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 10 TO 20%:-

The soil sample for the range of 10 to 20% moisture content is prepared and the measurement of the capacitance of the capacitive probe sensor is done on the soil sample. The moisture content corresponding to the capacitance measured by the impedance/spectrum analyzer at a region of the soil sample is also measured by the POGO soil moisture sensor.

VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 10 TO 20%:-

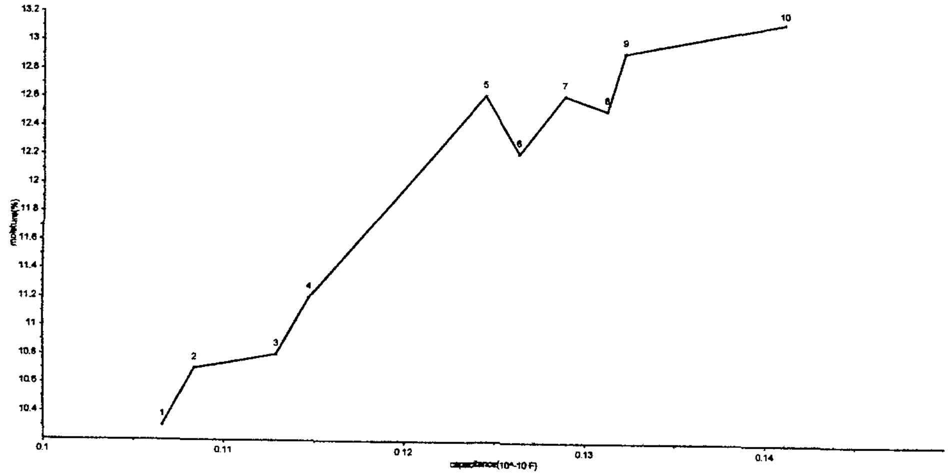


Fig.7.8 Moisture vs capacitance

tal tance ured ^{0} F)	Capacitance of the connection cables (10^{-10} F)	Total Capacitance of the electrode inside the plastic electrode holder and in the air (10^{-10} F)	Difference of the capacitances (10^{-10} F)	Actual capacitance of the electrode (10^{-10} F)	Moisture (%)	Calibrated moisture (%)	Error (10^{-1})	Pe cer tag erro
8220	0.55176	0.02834	0.10209	0.10664	10.3	10.284	1.5998	0.15 31
8398	0.55176	0.02834	0.10388	0.10838	10.7	10.519	1.8148	1.69 07
8860	0.55176	0.02834	0.10849	0.11289	10.8	11.081	-2.8136	2.60 1
9045	0.55176	0.02834	0.11034	0.11470	11.2	11.289	-0.88549	0.79 6
0048	0.55176	0.02834	0.12037	0.12448	12.6	12.232	3.6807	2.92 15
0237	0.55176	0.02834	0.12227	0.12633	12.2	12.376	-1.7575	1.44 5
0496	0.55176	0.02834	0.12486	0.12886	12.6	12.555	0.44869	0.35 10
0735	0.55176	0.02834	0.12725	0.13119	12.5	12.702	-2.0222	1.61 7
0838	0.55176	0.02834	0.12828	0.13220	12.9	12.761	1.3945	1.08 00
1739	0.55176	0.02834	0.13728	0.14099	13.1	13.132	-0.31948	0.24 8

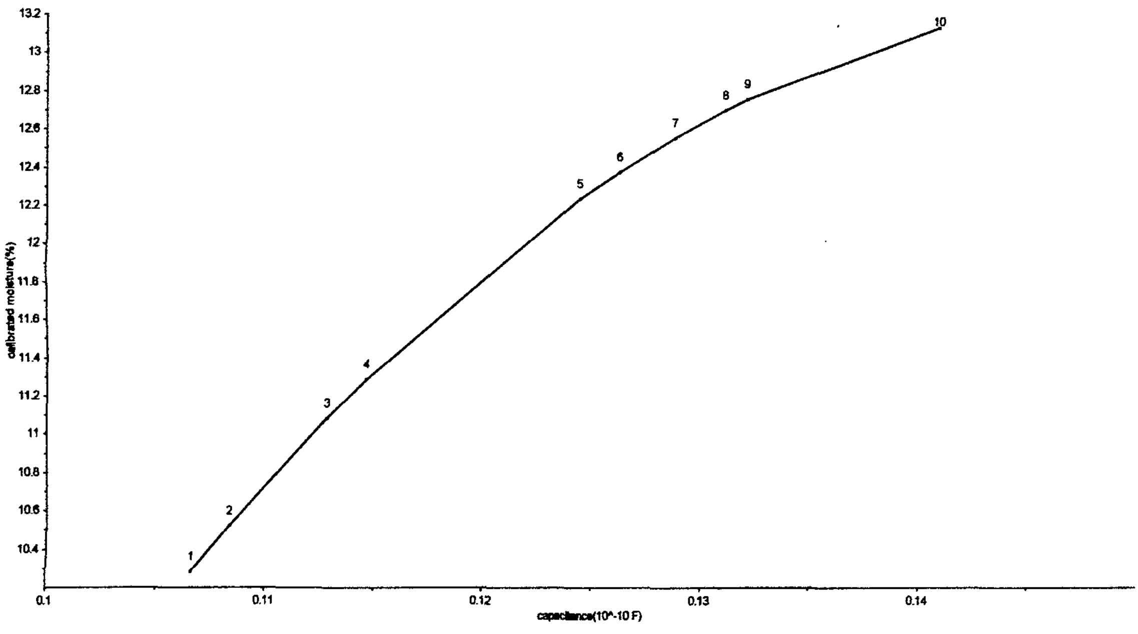


Fig.7.9 Calibrated moisture vs capacitance

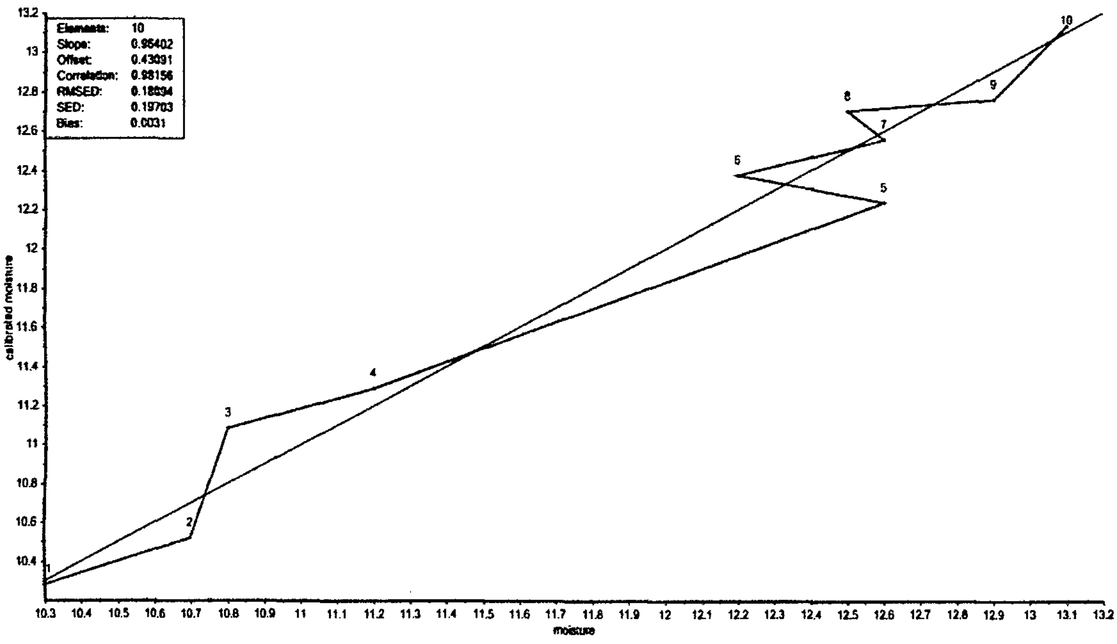


Fig.7.10 Calibrated moisture vs moisture

The graph shows that the correlation coefficient is close to 1 equal to 0.98156. The slope is close to 1 equal to 0.96402. The offset is low equal to 0.43091. The root mean square error of deviation RMSED, the squared error of deviation SED and the bias are close to 0 equal to 0.18694, 0.19703 and 0.0031. Thus the relationship between the calibrated moisture and moisture is highly linear.

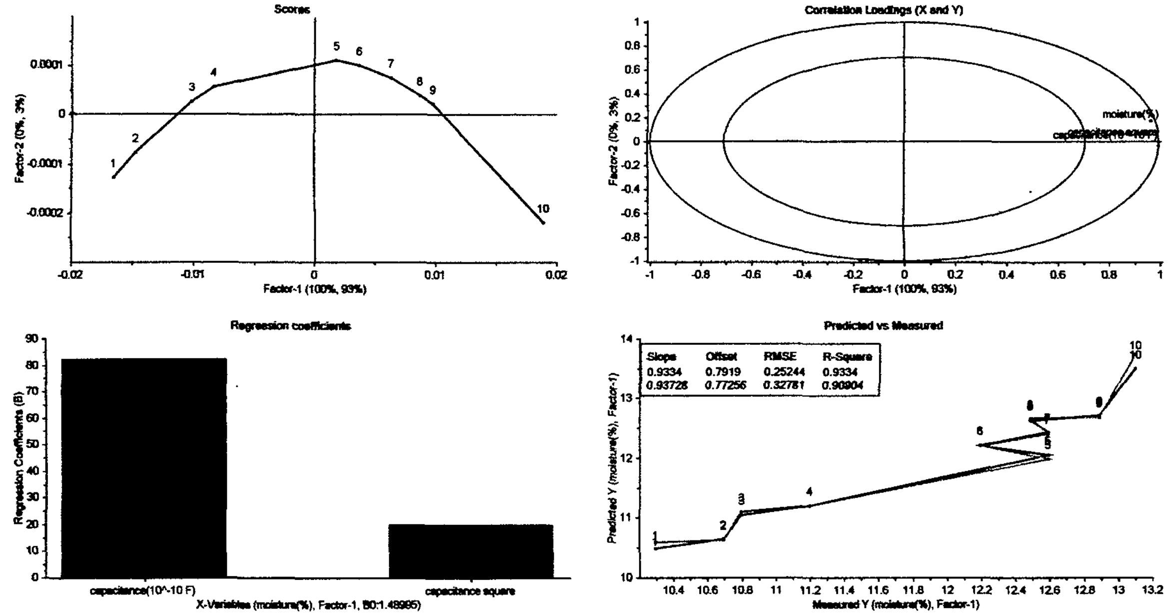


Fig.7.11 Regression between the moisture and capacitance for Factor 1

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the range of 10 to 20% moisture content is obtained by using Partial Least Squares or Projection to Latent Structures regression method.

1. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 1:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 1 shows one outlier 10 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

2. LOADINGS PLOT:-

The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The moisture is also on the same direction from the centre of the plot and close to the capacitance and capacitance square. The Y-variable shows 93% explained variance along the factor 1 and 3% explained variance along the factor 2. Thus the moisture is highly positively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are 20.01, 82.31, 1.48895.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.9334 and 0.90904. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.25244 and 0.32781. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 0.7919 and 0.77256. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.9334 and 0.93728.

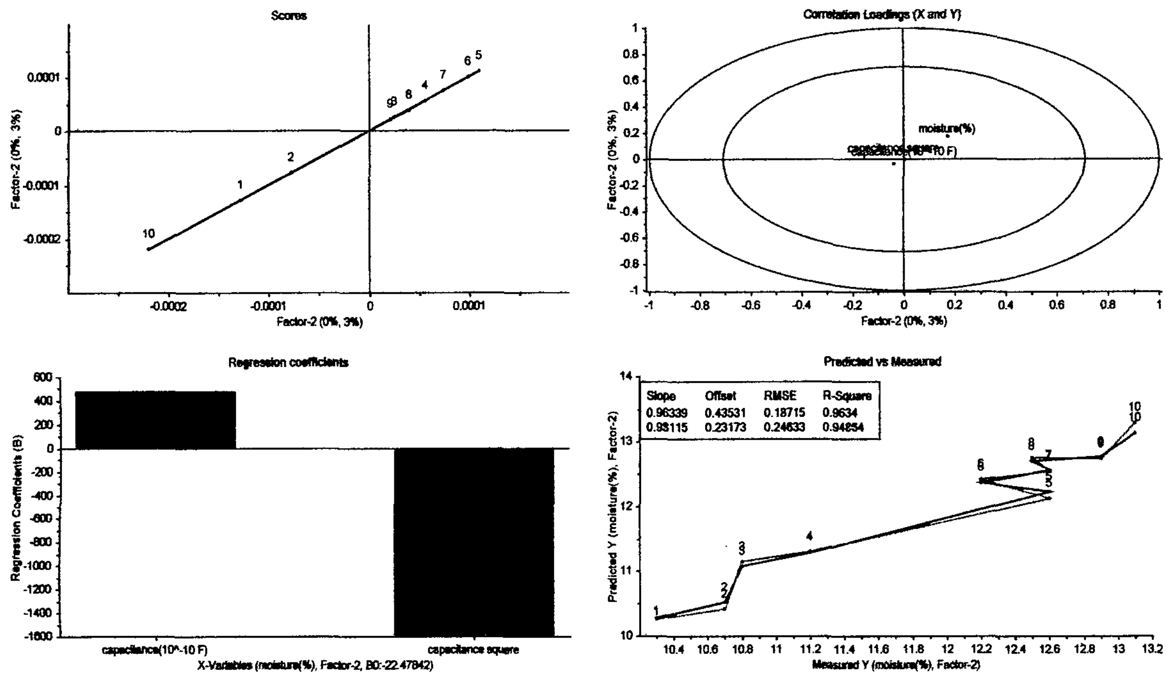


Fig.7.12 Regression between the moisture and capacitance for Factor 2

2. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 2 shows one outlier 1 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

5. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The moisture and capacitance square are also on the same direction from the centre of the plot. The moisture and capacitance are in opposite direction from the centre of the plot. The moisture is not close to the capacitance and the capacitance square. The Y-variable shows 93% explained variance along the factor 1 and 3% explained variance along the factor 2. Thus the moisture is not highly positively correlated to the capacitance square and not highly negatively correlated to the capacitance for factor 2.

6. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are -1591, 476.9, -22.47842.

7. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.9634 and 0.94864. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.18715 and 0.24633. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 0.43531 and 0.23173. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.96339 and 0.98115.

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 10 to 20% moisture content is

$$\theta_v = -1591*C^2 + 476.9*C - 22.47842$$

θ_v = moisture (%)

C = capacitance (10^{-10} F)

8. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 20 TO 30%:-

The soil sample for the range of 20 to 30% moisture content is prepared and the measurement of the capacitance of the capacitive probe sensor is done on the soil sample. The moisture content corresponding to the capacitance measured by the impedance/spectrum analyzer at a region of the soil sample is also measured by the POGO soil moisture sensor.

VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 20 TO 30%:-

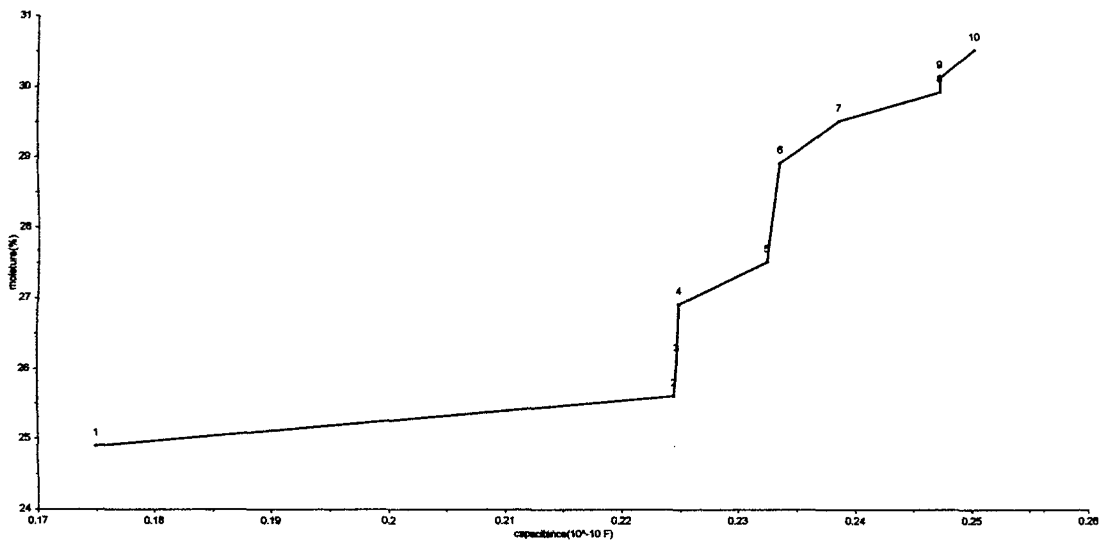


Fig.7.13 Moisture vs capacitance

Total capacitance measured (10^{-10} F)	Capacitance of the connection cables (10^{-10} F)	Total Capacitance of the electrode inside the plastic electrode holder and in the air (10^{-10} F)	Difference of the capacitances (10^{-10} F)	Actual capacitance of the electrode (10^{-10} F)	Moisture (%)	Calibrated moisture (%)	Error	Per cen tage error
0.75223	0.55176	0.02834	0.17212	0.174992	24.9	23.63592	-1.26408	-5.07661
0.80289	0.55176	0.02834	0.22279	0.22444	25.6	27.54321	1.943212	7.590674
0.80315	0.55176	0.02834	0.22305	0.224693	26.1	27.56361	1.463607	5.607691
0.80335	0.55176	0.02834	0.22325	0.22489	26.9	27.57943	0.679433	2.525774
0.81109	0.55176	0.02834	0.23099	0.232442	27.5	28.1891	0.689097	2.505809
0.81220	0.55176	0.02834	0.23209	0.233524	28.9	28.27674	-0.62326	-2.15662
0.81737	0.55176	0.02834	0.23726	0.238567	29.5	28.68604	-0.81396	-2.7592
0.82626	0.55176	0.02834	0.24615	0.247247	29.9	29.39403	-0.50597	-1.69222
0.82627	0.55176	0.02834	0.24616	0.247254	30.1	29.39462	-0.70538	-2.34345
0.82926	0.55176	0.02834	0.24916	0.250177	30.5	29.63399	-0.86601	-2.83936

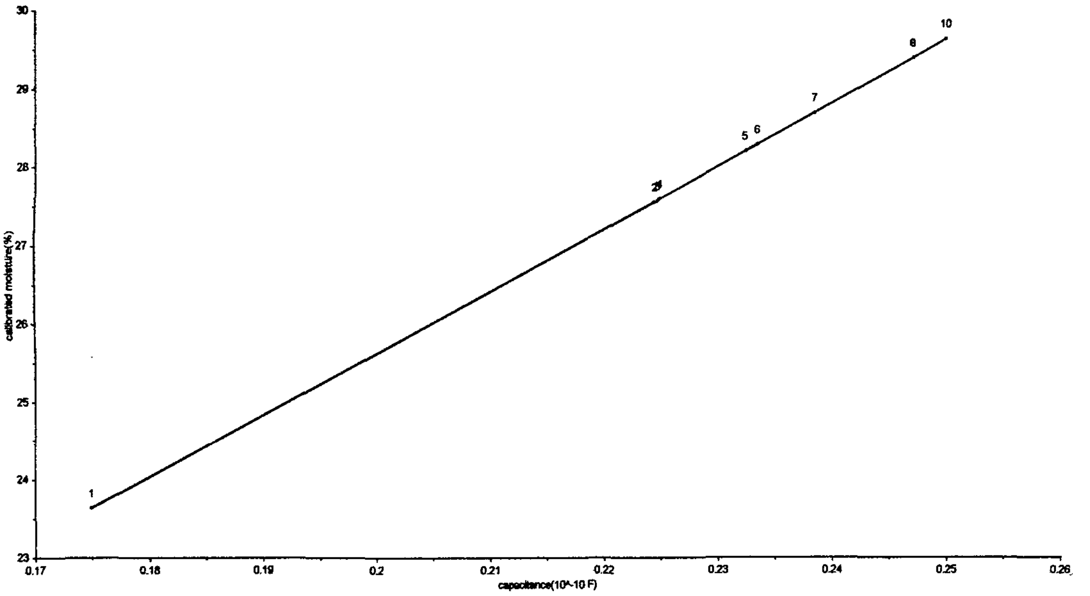


Fig.7.14 Calibrated moisture vs capacitance

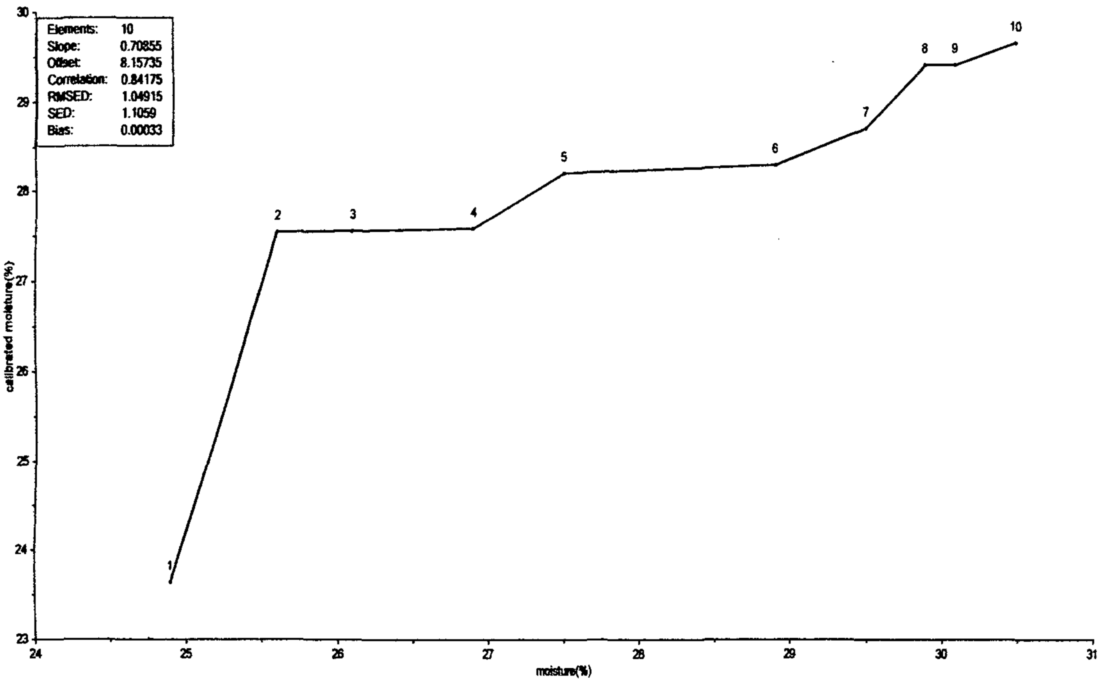


Fig.7.15 Calibrated moisture vs moisture

The graph shows that the correlation coefficient is close to 1 equal to 0.84175. The slope is close to 1 equal to 0.70855. The offset is high equal to 8.15735. The root mean square error of deviation RMSED and the squared error of deviation SED are not very close to 0 equal to 1.04915 and 1.1059. The bias is close to 0 equal to 0.00033. Thus the relationship between the calibrated moisture and moisture is highly linear.

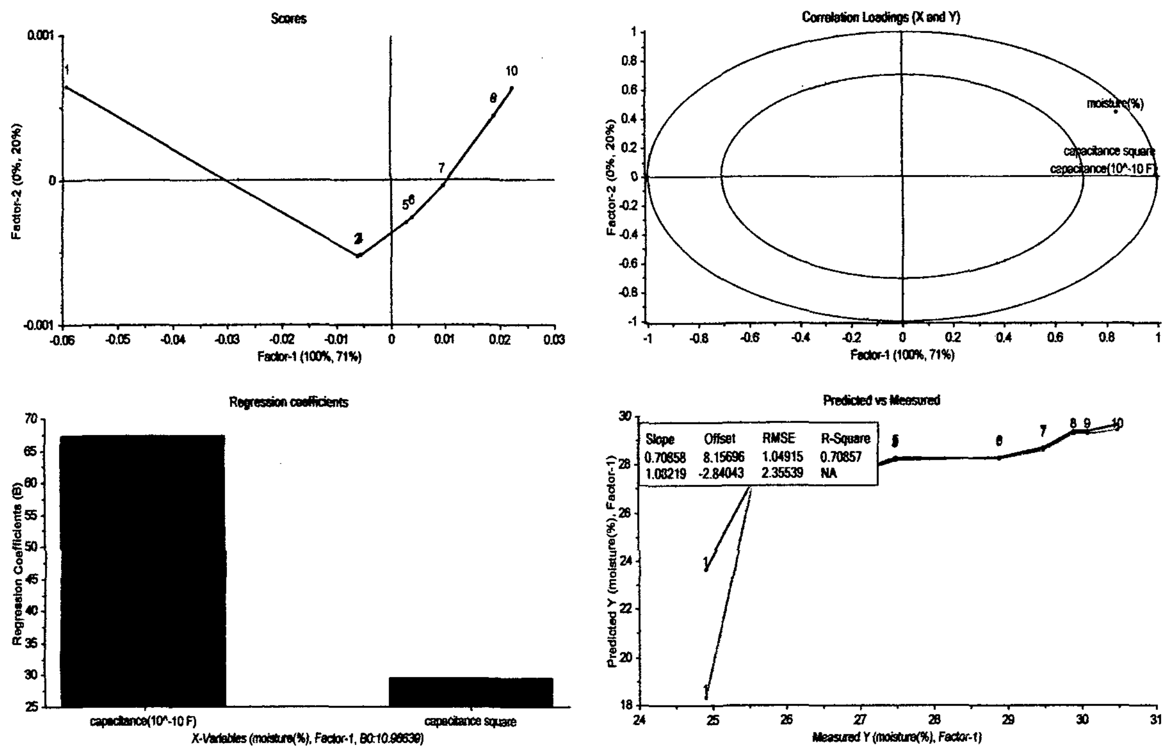


Fig.7.16 Regression between the moisture and capacitance for Factor 1

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the range of 20 to 30% moisture content is obtained by using Partial Least Squares or Projection to Latent Structures regression method.

1. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 1:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 1 shows one outlier 1 in the samples. This outlier does not belong to the group of the samples because it does not form the pattern with the group of the samples.

2. LOADINGS PLOT:-

The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The moisture is also on the same direction from the centre of the plot and close to the capacitance and capacitance square. The Y-variable shows 71% explained variance along the factor 1 and 20% explained variance along the factor 2. Thus the moisture is highly positively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are 29.49, 67.24, 10.96639.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficient corresponding to calibration equation is close to 1 equal to 0.70857. The correlation coefficient corresponding to validation of the calibration equation is not shown because it is not close to 1 and is low. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are not close to 0 equal to 1.04915 and 2.35539. The offsets corresponding to calibration equation and validation of calibration equation are high equal to 8.15696 and -2.8043. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.70858 and 1.08219.

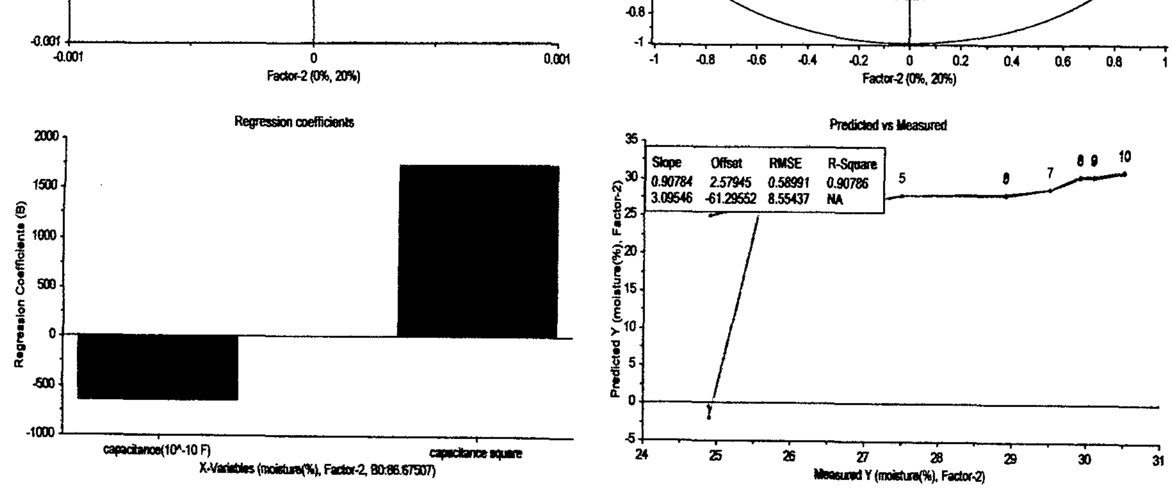


Fig.7.17 Regression between the moisture and capacitance for Factor 2

2. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

nd reduce the linearity of the relationship between the calibrated moisture and moisture. The scores plot for factor 2 shows one outlier 1 in the samples. This outlier does not belong to the group of the samples because it does not form the pattern with the group of the samples.

2. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The moisture and capacitance square are also on the same direction from the centre of the plot. The moisture and capacitance are in opposite direction from the centre of the plot. The moisture is not close to the capacitance and the capacitance square. The Y-variable shows 71% explained variance along the factor 1 and 20% explained variance along the factor 2. Thus the moisture is not highly positively correlated to the capacitance square and not highly negatively correlated to the capacitance for factor 2.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are 1731, -656.3, -86.67507.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficient corresponding to calibration equation is close to 1 equal to 0.90786. The correlation coefficient corresponding to validation of the calibration equation is not shown because it is not close to 1 and is low. The RMSEC corresponding to calibration equation is close to 0 equal to 0.58991. The RMSEP corresponding to validation of calibration equation is high equal to 8.55437. The offsets corresponding to calibration equation and validation of calibration equation are high equal to 2.57945 and -61.29552. The slope corresponding to calibration equation is close to 1 equal to 0.90784. The slope corresponding to validation of calibration equation is high equal to 3.09546.

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 1 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 20 to 30% moisture content is

$$\theta_v = 29.49*C^2 + 67.24*C + 10.96639$$

θ_v = moisture (%)

C = capacitance (10^{-10} F)

5. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 30 TO 40%:-

The soil sample for the range of 30 to 40% moisture content is prepared and the measurement of the capacitance of the capacitive probe sensor is done on the soil sample. The moisture content corresponding to the capacitance measured by the impedance/spectrum analyzer at a region of the soil sample is also measured by the POGO soil moisture sensor.

VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 30 TO 40%:-

Total capacitance measured (10^{-10} F)	Capacitance of the connection cables (10^{-10} F)	Total Capacitance of the electrode inside the plastic electrode holder and in the air (10^{-10} F)	Difference of the capacitances (10^{-10} F)	Actual capacitance of the electrode (10^{-10} F)	Moisture (%)	Calibrated moisture (%)	Error (10^{-1})	Percentage error
0.86929	0.55176	0.02834	0.28919	0.28925	28.6	28.952	-3.5201	-1.2308
0.90592	0.55176	0.02834	0.32581	0.324993	35.2	34.435	7.6515	2.1737
0.91607	0.55176	0.02834	0.33597	0.334906	35.6	35.418	1.8182	0.51074
0.92431	0.55176	0.02834	0.34421	0.342947	35.8	36.045	-2.4451	-0.68298
0.93544	0.55176	0.02834	0.35534	0.353808	36.4	36.647	-2.4680	-0.67802
0.94264	0.55176	0.02834	0.36254	0.360837	36.5	36.887	-3.8730	-1.0611
0.94351	0.55176	0.02834	0.36341	0.361686	36.5	36.908	-4.0839	-1.1189
0.94885	0.55176	0.02834	0.36875	0.366901	36.6	37.001	-4.0053	-1.0943
0.95862	0.55176	0.02834	0.37851	0.376428	36.7	37.002	-3.0214	-0.82326
0.966	0.55176	0.02834	0.38615	0.383879	37.5	36.853	6.4675	1.7247

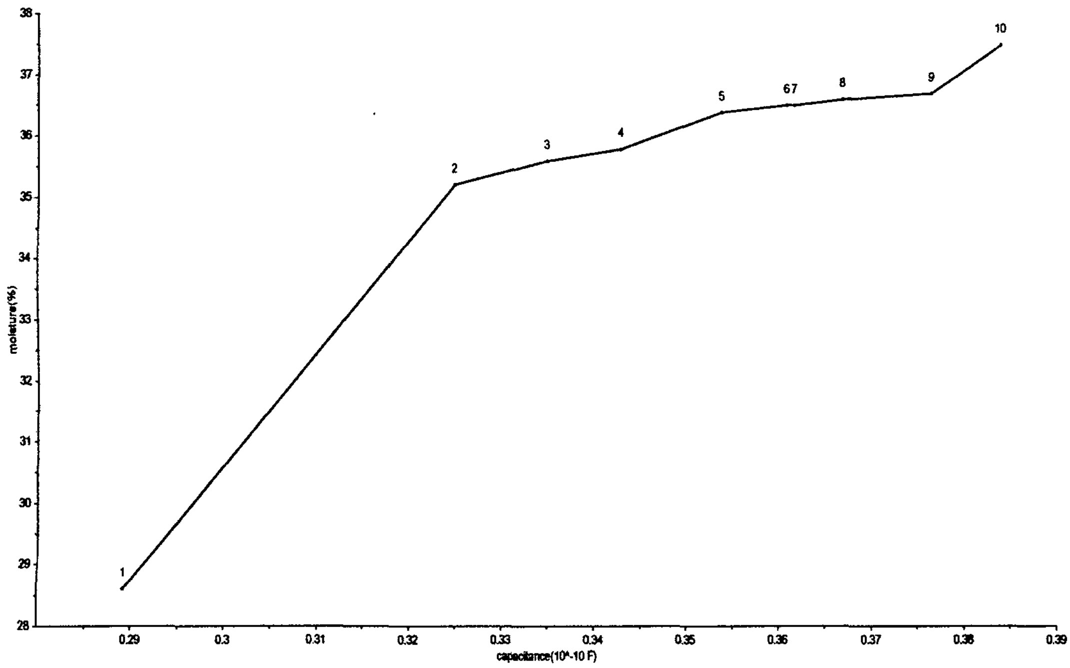


Fig.7.18 Moisture vs capacitance

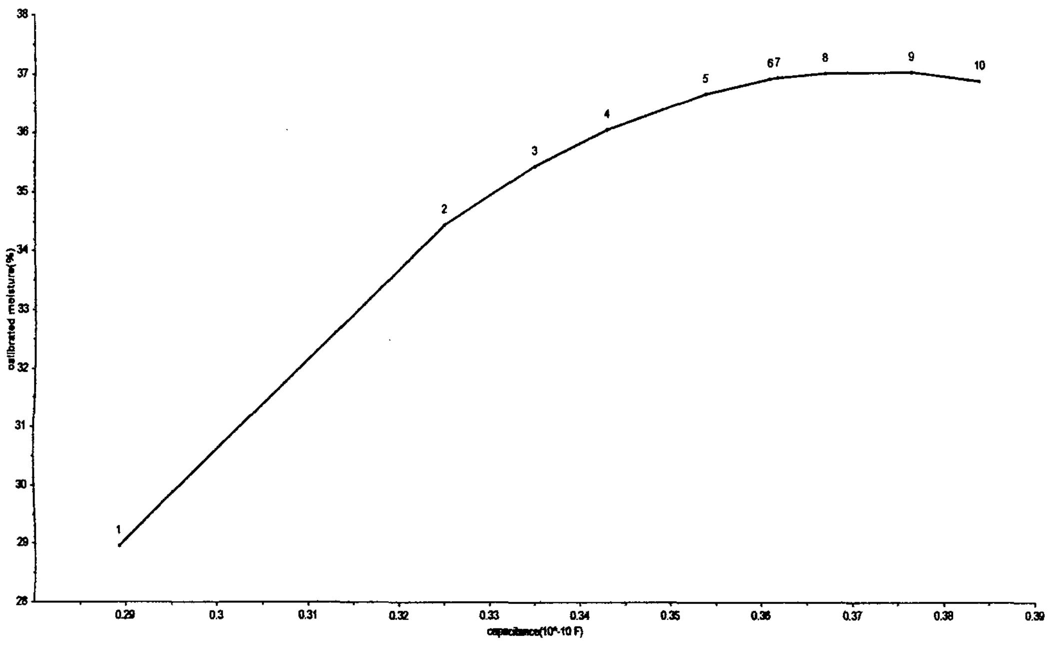


Fig.7.19 Calibrated moisture vs capacitance

The graph shows that the correlation coefficient is close to 1 equal to 0.98422. The slope is close to 1 equal to 0.97125. The offset is high equal to 1.09664. The root mean square error of deviation RMSED, the squared error of deviation SED and the bias are close to 0 equal to 0.43013, 0.44649 and 0.0748. Thus the relationship between the calibrated moisture and moisture is highly linear.

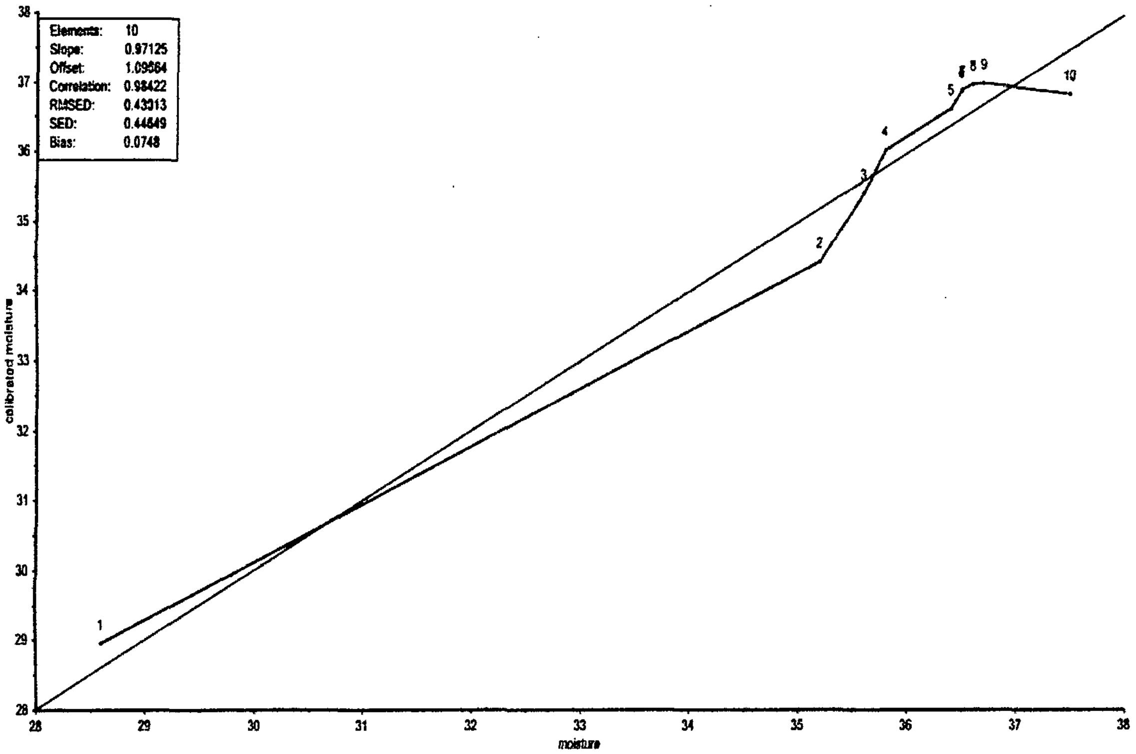


Fig.7.20 Calibrated moisture vs moisture

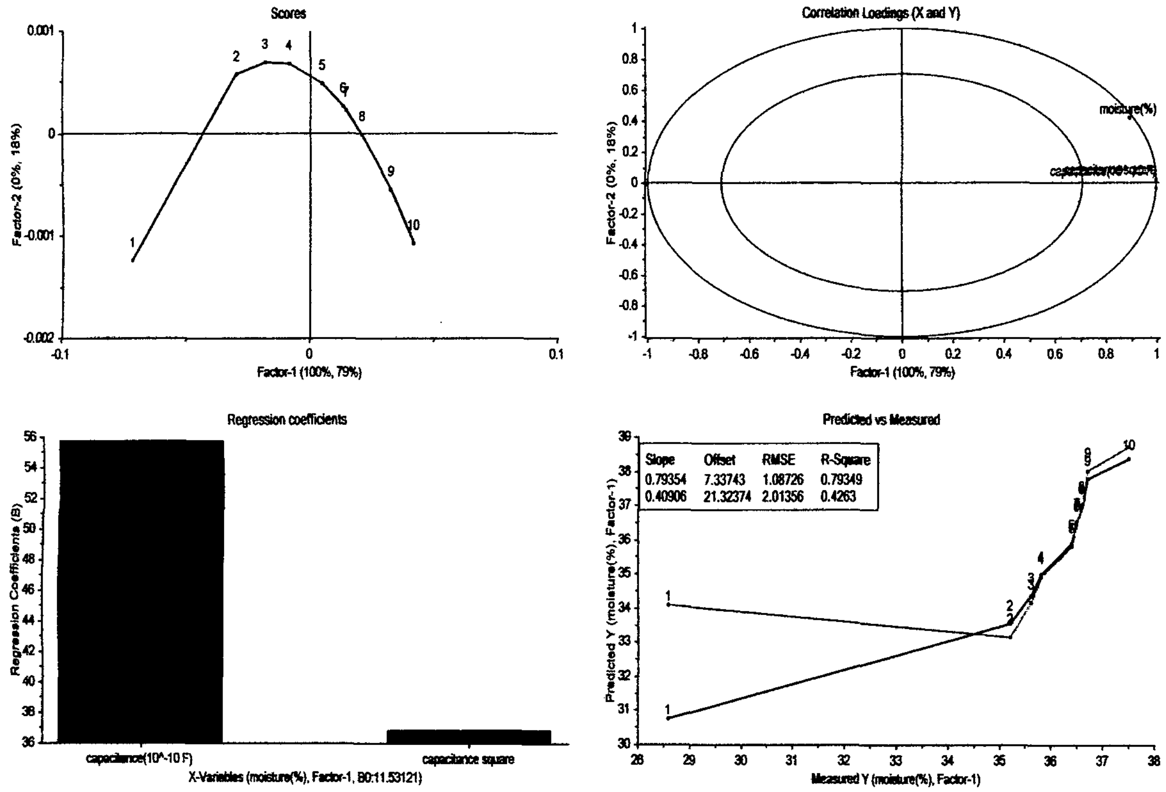


Fig.7.21 Regression between the moisture and capacitance for Factor 1

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the range of 30 to 40% moisture content is obtained by using Partial Least Squares or Projection to Latent Structures regression method.

1. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 1:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 1 shows one outlier 1 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

2. LOADINGS PLOT:-

The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The moisture is also on the same direction from the centre of the plot and close to the capacitance and capacitance square. The Y-variable shows 79% explained variance along the factor 1 and 18% explained variance along the factor 2. Thus the moisture is highly positively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are 36.83, 55.73, 11.53121.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficient corresponding to calibration equation is close to 1 equal to 0.79349. The correlation coefficient corresponding to validation of the calibration equation is not close to 1 equal to 0.4263. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are not close to 0 equal to 1.08726 and 2.01356. The offsets corresponding to calibration equation and validation of calibration equation are high equal to 7.33743 and 21.32374. The slope corresponding to calibration equation is close to 1 equal to 0.79354. The slope corresponding to validation of calibration equation is low equal to 0.40906.

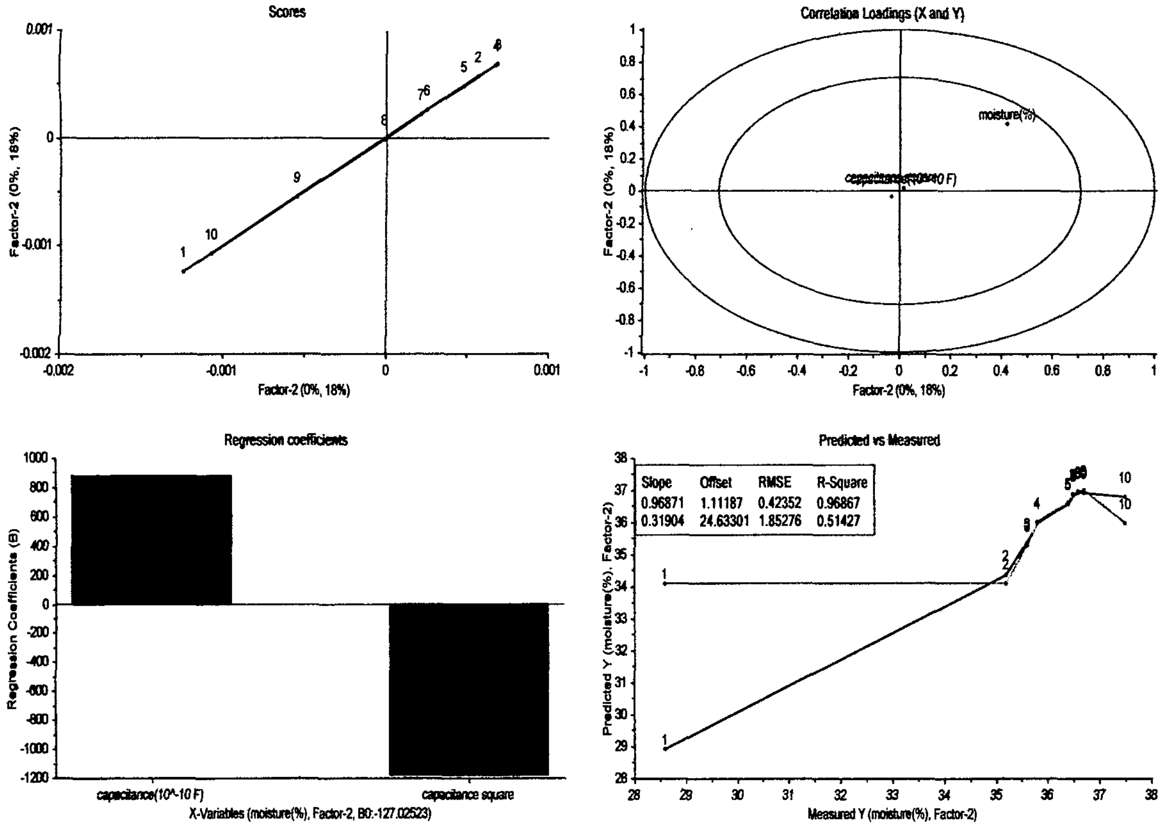


Fig.7.22 Regression between the moisture and capacitance for Factor 2

2. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 2 shows one outlier 1 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

2. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The moisture and capacitance square are also on the same direction from the centre of the plot. The moisture and capacitance are in opposite direction from the centre of the plot. The moisture is not close to the capacitance and the capacitance square. The Y-variable shows 79% explained variance along the factor 1 and 18% explained variance along the factor 2. Thus the moisture is not highly positively correlated to the capacitance square and not highly negatively correlated to the capacitance for factor 2.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are -1187, 882.5, -127.02523.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficient corresponding to calibration equation is close to 1 equal to 0.96867. The correlation coefficient corresponding to validation of the calibration equation is not close to 1 equal to 0.51427. The RMSEC corresponding to calibration equation is close to 0 equal to 0.42352. The RMSEP corresponding to validation of calibration equation is not close to 0 equal to 1.85276. The offset corresponding to calibration equation is low equal to 1.11187. The offset corresponding to validation of calibration equation is high equal to 24.63301. The slope corresponding to calibration equation is close to 1 equal to 0.96871. The slope corresponding to validation of calibration equation is low equal to 0.31904.

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 30 to 40% moisture content is

$$\theta_v = -1187*C^2 + 882.5*C - 127.02523$$

θ_v = moisture (%)

C = capacitance (10^{-10} F)

5. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 40 TO 50%:-

The soil sample for the range of 40 to 50% moisture content is prepared and the measurement of the capacitance of the capacitive probe sensor is done on the soil sample. The moisture content corresponding to the capacitance measured by the impedance/spectrum analyzer at a region of the soil sample is also measured by the POGO soil moisture sensor.

VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 40 TO 50%:-

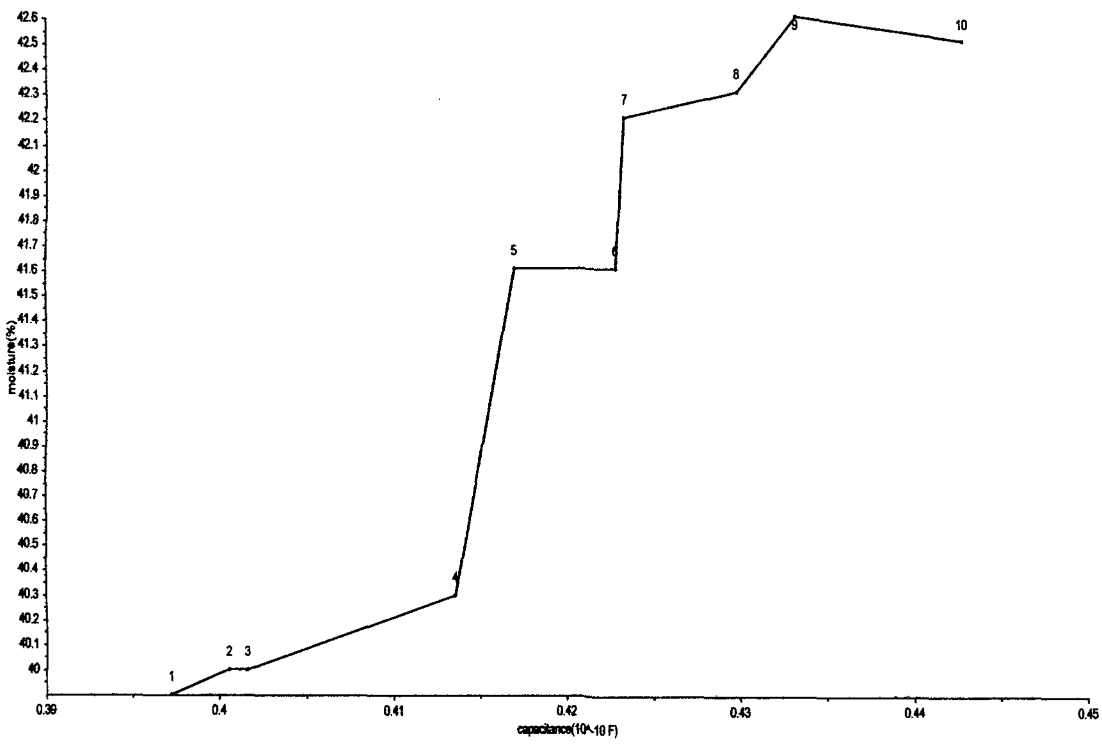


Fig.7.23 Moisture vs capacitance

Total capacitance measured (10^{-10} F)	Capacitance of the connection cables (10^{-10} F)	Total Capacitance of the electrode inside the plastic electrode holder and in the air (10^{-10} F)	Difference of the capacitances (10^{-10} F)	Actual capacitance of the electrode (10^{-10} F)	Moisture (%)	Calibrated moisture (%)	Error	Percentage error
0.97994	0.55176	0.02834	0.39984	0.39724	39.9	39.83993	0.060073	0.150559
0.98330	0.55176	0.02834	0.40320	0.40053	40	40.06595	-0.06595	-0.16487
0.98441	0.55176	0.02834	0.40431	0.40161	40	40.1406	-0.1406	-0.3515
0.99661	0.55176	0.02834	0.41651	0.41352	40.3	40.96787	-0.66787	-1.65724
1.0001	0.55176	0.02834	0.42003	0.41695	41.6	41.20819	0.391806	0.94184
1.0061	0.55176	0.02834	0.42600	0.42277	41.6	41.61772	-0.01772	-0.04259
1.0066	0.55176	0.02834	0.42652	0.42328	42.2	41.65345	0.546554	1.295151
1.0133	0.55176	0.02834	0.43315	0.42975	42.3	42.11179	0.188211	0.444943
1.0167	0.55176	0.02834	0.43665	0.43317	42.6	42.35459	0.245406	0.57607
1.0266	0.55176	0.02834	0.44648	0.44276	42.5	43.0413	-0.5413	-1.27364

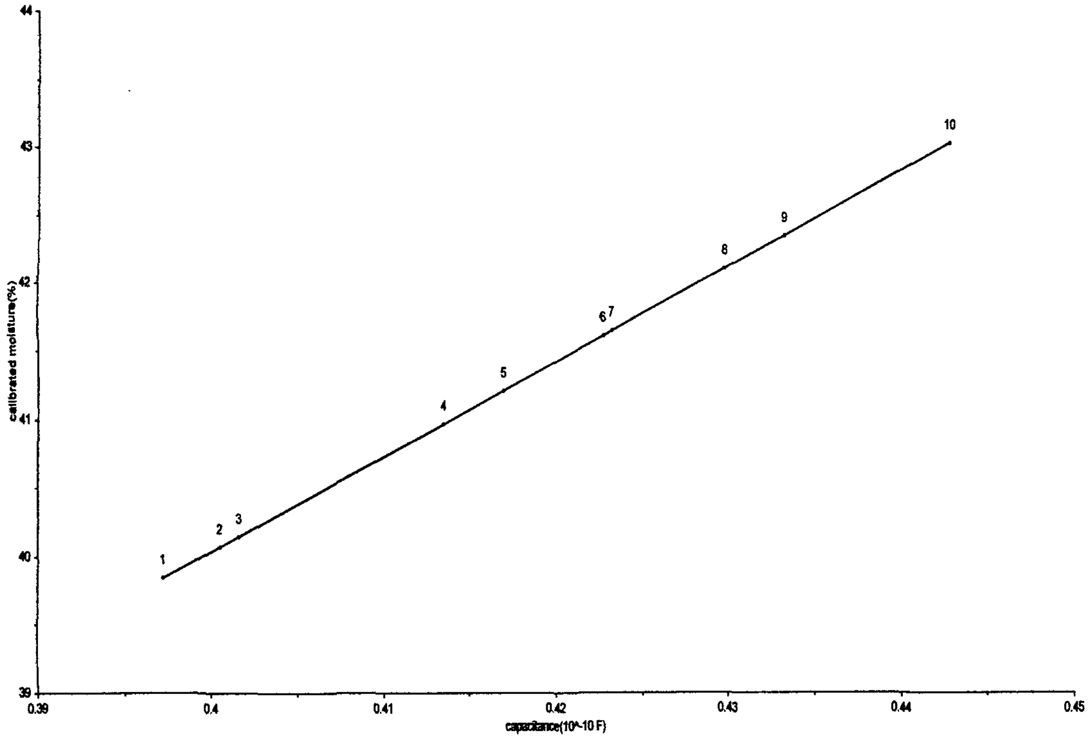


Fig.7.24 Calibrated moisture vs capacitance

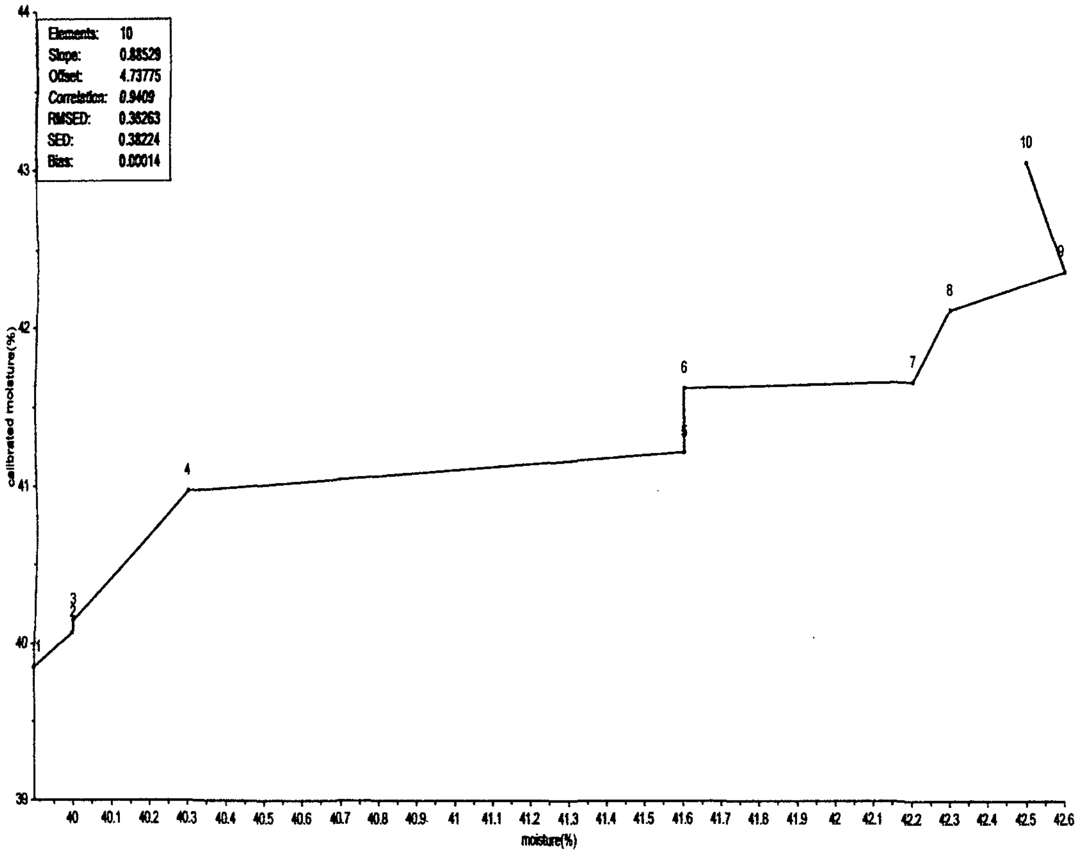


Fig.7.25 Calibrated moisture vs moisture

The graph shows that the correlation coefficient is close to 1 equal to 0.9409. The slope is close to 1 equal to 0.88529. The offset is high equal to 4.73775. The root mean square error of deviation RMSED, the squared error of deviation SED and the bias are close to 0 equal to 0.36263, 0.38224 and 0.00014. Thus the relationship between the calibrated moisture and moisture is highly linear.

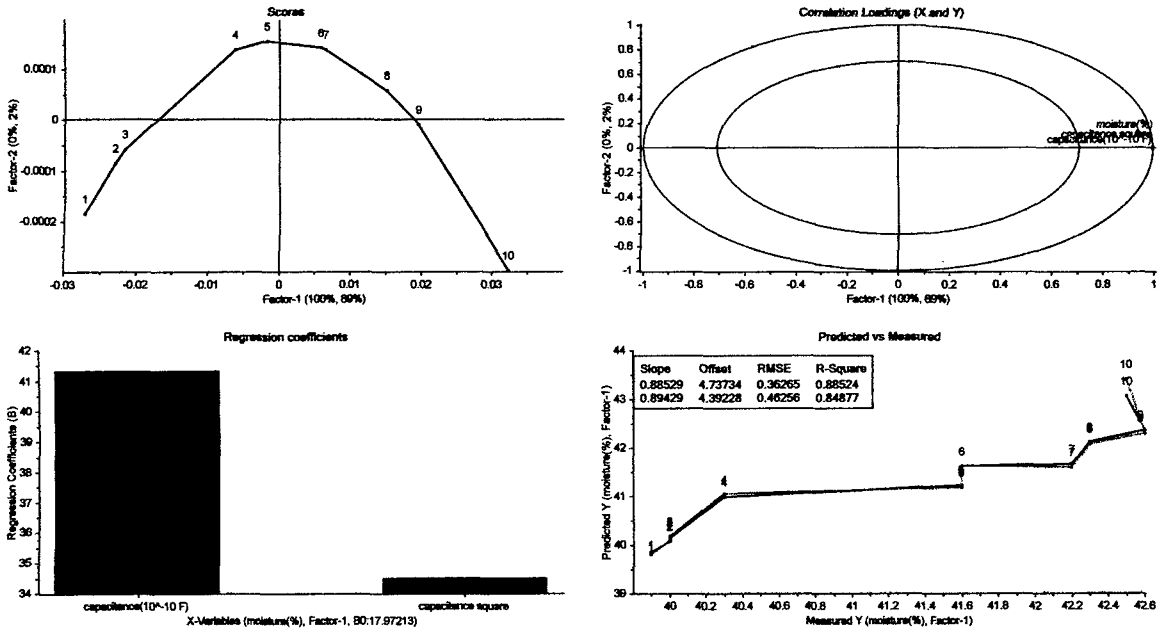


Fig.7.26 Regression between the moisture and capacitance for Factor 1

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the range of 40 to 50% moisture content is obtained by using Partial Least Squares or Projection to Latent Structures regression method.

1. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 1:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 1 shows one outlier 10 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

2. LOADINGS PLOT:-

The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The moisture is also on the same direction from the centre of the plot and close to the capacitance and capacitance square. The Y-variable shows 89% explained variance along the factor 1 and 2% explained variance along the factor 2. Thus the moisture is highly positively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are 34.51, 41.34, 17.97213.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.88524 and 0.84877. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.36265 and 0.46256. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 4.73734 and 4.39228. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.88529 and 0.89429.

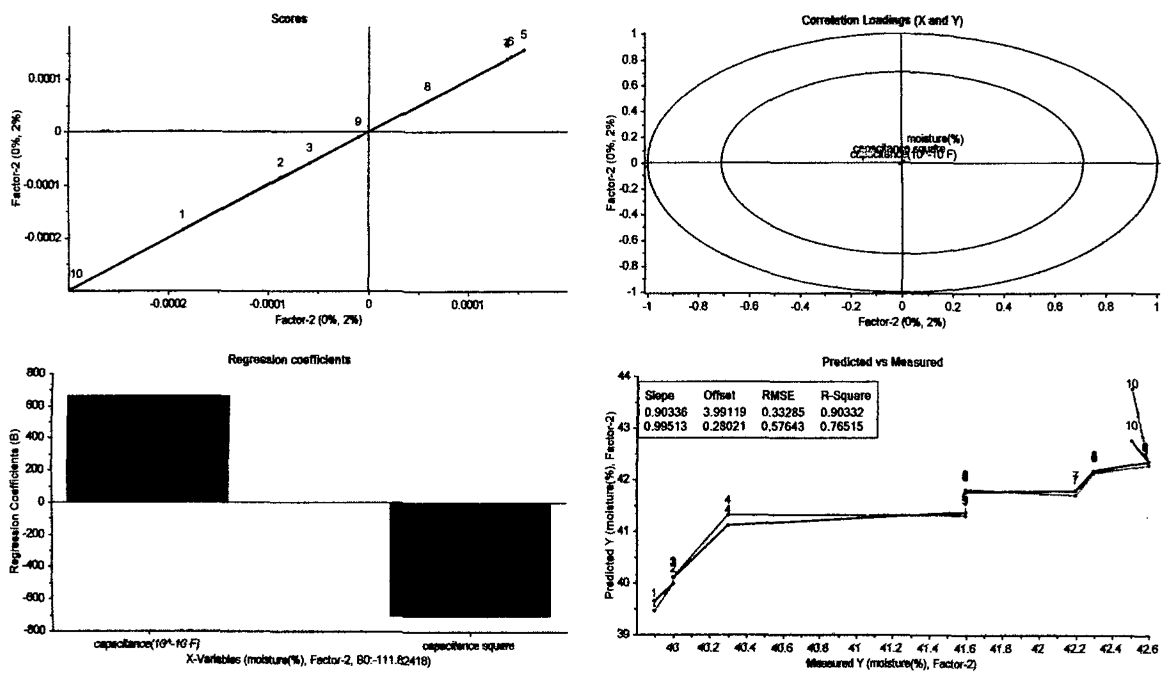


Fig.7.27 Regression between the moisture and capacitance for Factor 2

2. REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 2 shows on outlier 10 in the samples. This outlier belong to the group of the samples because samples are missing between the group of the samples and outlier.

2. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The moisture and capacitance square are also on the same direction from the centre of the plot. The moisture and capacitance are in opposite direction from the centre of the plot. The moisture is not close to the capacitance and the capacitance square. The Y-variable shows 89% explained variance along the factor 1 and 2% explained variance along the factor 2. Thus the moisture is not highly positively correlated to the capacitance square and not highly negatively correlated to the capacitance for factor 2.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are -707.8, 662.5, -111.82118.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.90332 and 0.76515. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.33285 and 0.57643. The offset corresponding to calibration equation is high equal to 3.99119. The offset corresponding to validation of calibration equation is low equal to 0.28021. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.90336 and 0.99513.

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation are comparable and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 1 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 40 to 50% moisture content is

$$\theta_v = 34.51*C^2 + 41.34*C + 17.97213$$

θ_v = moisture (%)

C = capacitance (10^{-10} F)

7.4 VARIATION OF THE FREQUENCY OF OSCILLATOR WITH CAPACITANCE OF THE CAPACITIVE PROBE SENSOR:-

The variation of the frequency of the oscillation of the Colpitts oscillator with the variation in the capacitance of the capacitive probe sensor is measured by the impedance/spectrum analyzer. The calibration equation for the Colpitts oscillator is determined by connecting the various standard capacitors in the range from 2 pF to 820 pF across the 100 pF capacitor C2 of the Colpitts oscillator. The output of the Colpitts oscillator is connected to the 50Ω S input of the impedance/spectrum analyzer. The impedance/spectrum analyzer is used in the spectrum mode to determine the output frequency of the Colpitts oscillator. When no capacitor is connected across the 100 pF capacitor C2 the impedance/spectrum analyzer shows two peaks 30.6 MHz at -21.337 dB gain and 61.2 MHz at -42.674 dB gain. The frequency 61.2 MHz is a harmonic frequency of the frequency 30.6 MHz of the Colpitts oscillator. When the capacitors are connected across the 100 pF capacitor C2 the frequency of the oscillation of the Colpitts oscillator decreases from 30.6 MHz and 61.2 MHz to lower values. Thus the measurement of the variation in the frequency of oscillation with variation in capacitance is done at both the frequencies 30.6 MHz and 61.2 MHz.

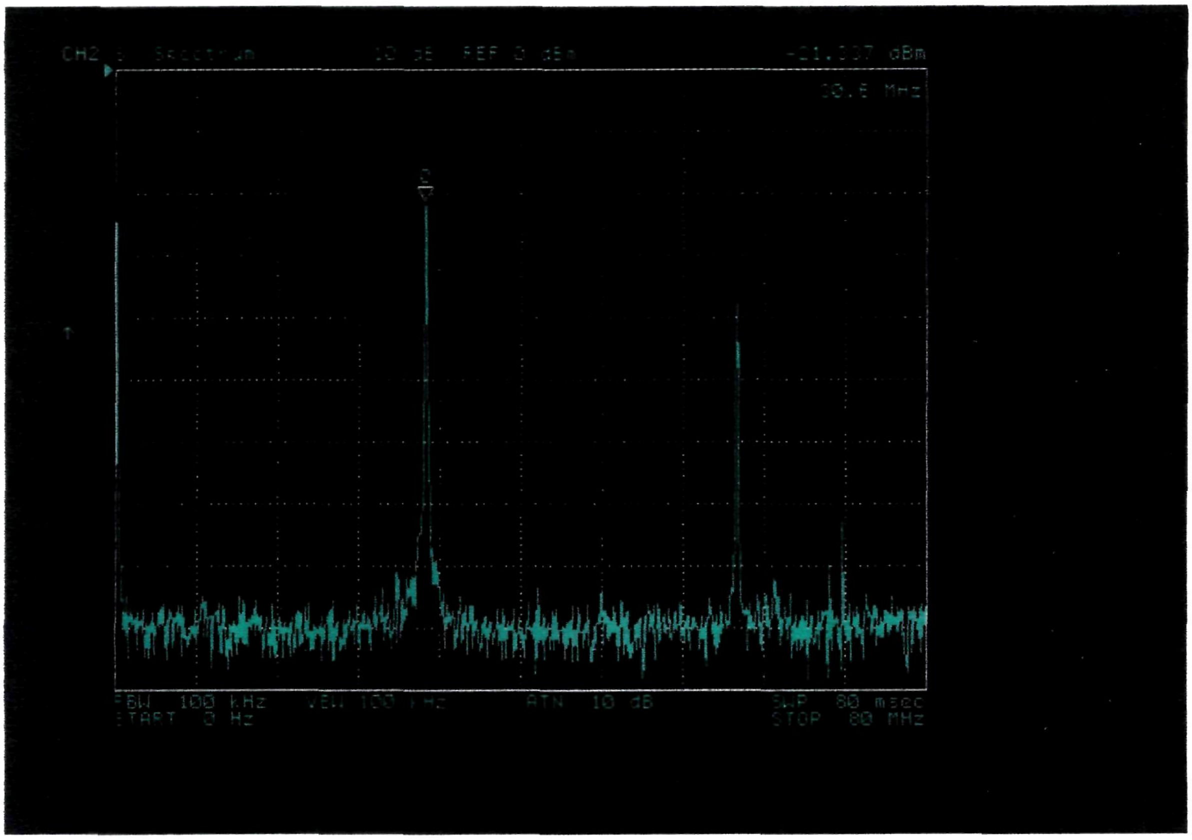


Fig.7.28 Frequency of oscillation of the Colpitts oscillator

1. VARIATION OF THE FREQUENCY OF OSCILLATOR WITH CAPACITANCE FOR 30.6 MHz FREQUENCY:-

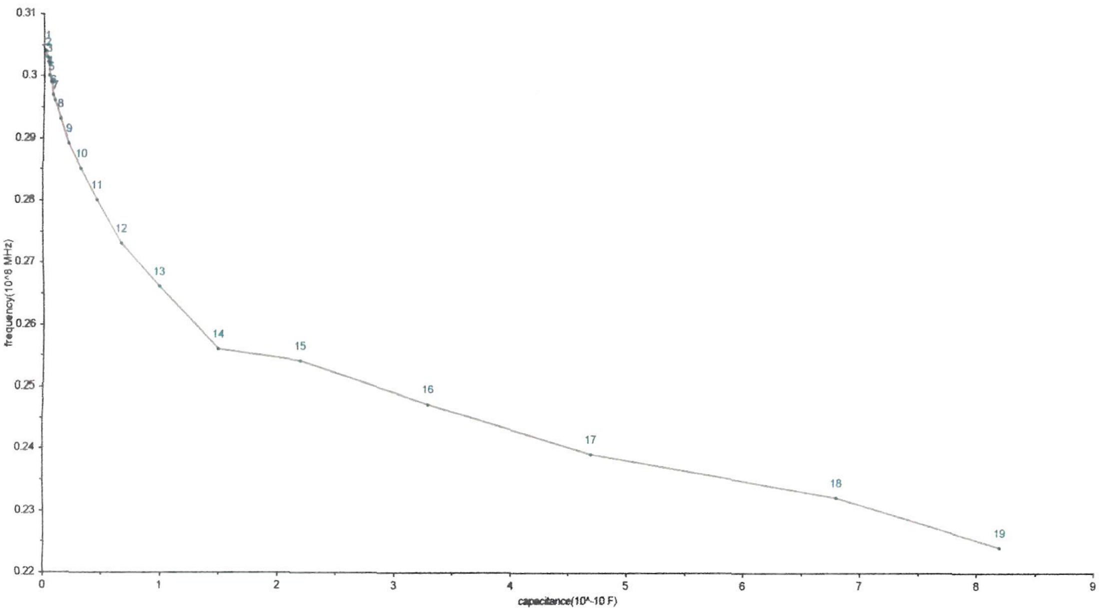


Fig.7.29 Frequency vs capacitance

Capacitance (10^{-10} F)	Frequency (10^8 Hz)	Calibrated frequency (10^8 Hz)	Error (10^8 Hz)	Percentage error
0.02	0.304	0.29556	0.00844	2.776184
0.03	0.303	0.295341	0.007659	2.527756
0.047	0.302	0.294968	0.007032	2.328408
0.05	0.3	0.294903	0.005097	1.699167
0.07	0.299	0.294465	0.004535	1.516756
0.08	0.297	0.294246	0.002754	0.927138
0.1	0.296	0.29381	0.00219	0.739865
0.15	0.293	0.292723	0.000277	0.09471
0.22	0.289	0.291208	-0.00221	-0.76415
0.33	0.285	0.288849	-0.00385	-1.35049
0.47	0.28	0.285881	-0.00588	-2.10032
0.68	0.273	0.281502	-0.0085	-3.11443
1	0.266	0.275	-0.009	-3.38346
1.5	0.256	0.26525	-0.00925	-3.61328
2.2	0.254	0.25244	0.00156	0.614173
3.3	0.247	0.23429	0.01271	5.145749
4.7	0.239	0.21469	0.02431	10.17155
6.8	0.232	0.19264	0.03936	16.96552
8.2	0.224	0.18284	0.04116	18.375

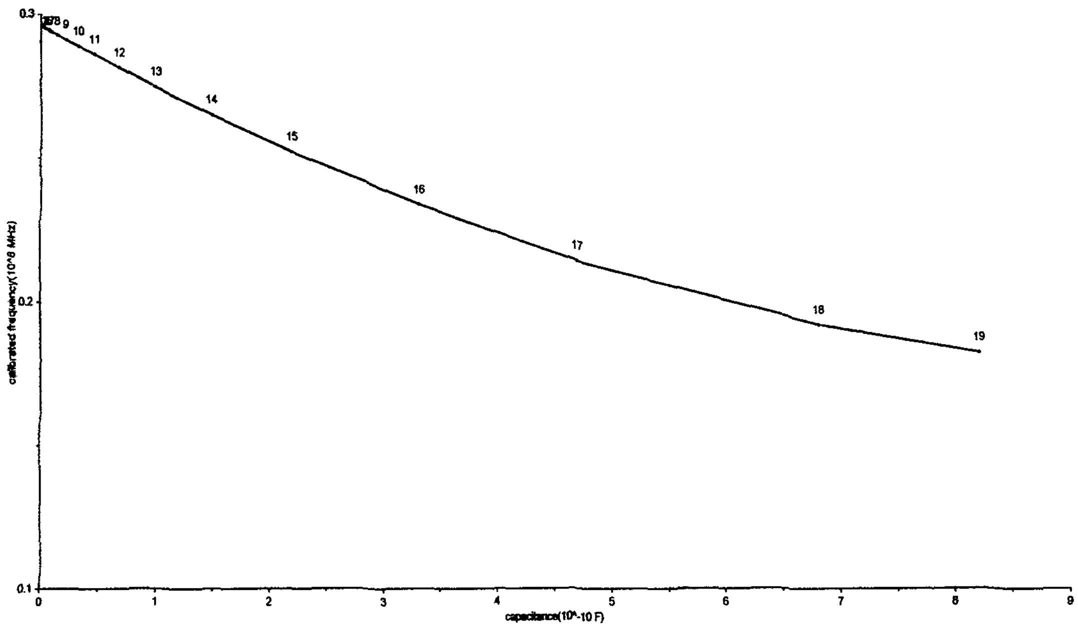


Fig.7.30 Calibrated frequency vs capacitance

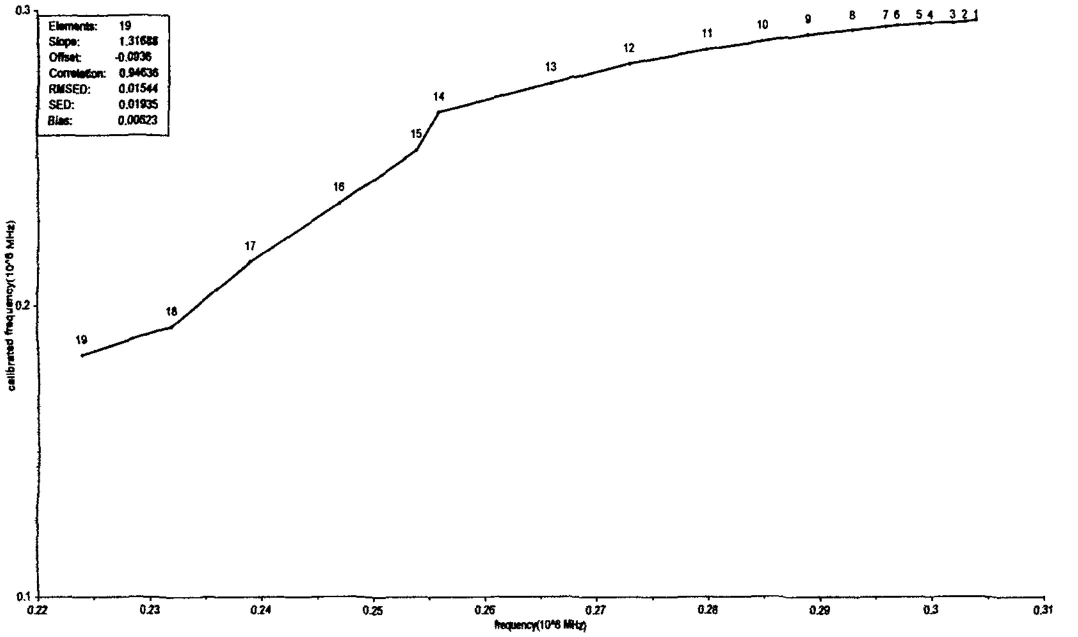


Fig.7.31 Calibrated moisture vs moisture

A graph is drawn between the calibrated moisture and moisture showing the relationship between the calibrated moisture and moisture. The relationship between the calibrated moisture and moisture should be linear with a slope equal to 1 and offset equal to 0. The graph shows that the correlation coefficient is close to 1 equal to 0.94636. The slope is close to 1 equal to 1.31688. The offset is low equal to -0.0936. The root mean square error of deviation RMSED, the squared error of deviation SED and the bias are close to 0 equal to 0.01544, 0.01935 and 0.00623. Thus the relationship between the calibrated moisture and moisture is highly linear.

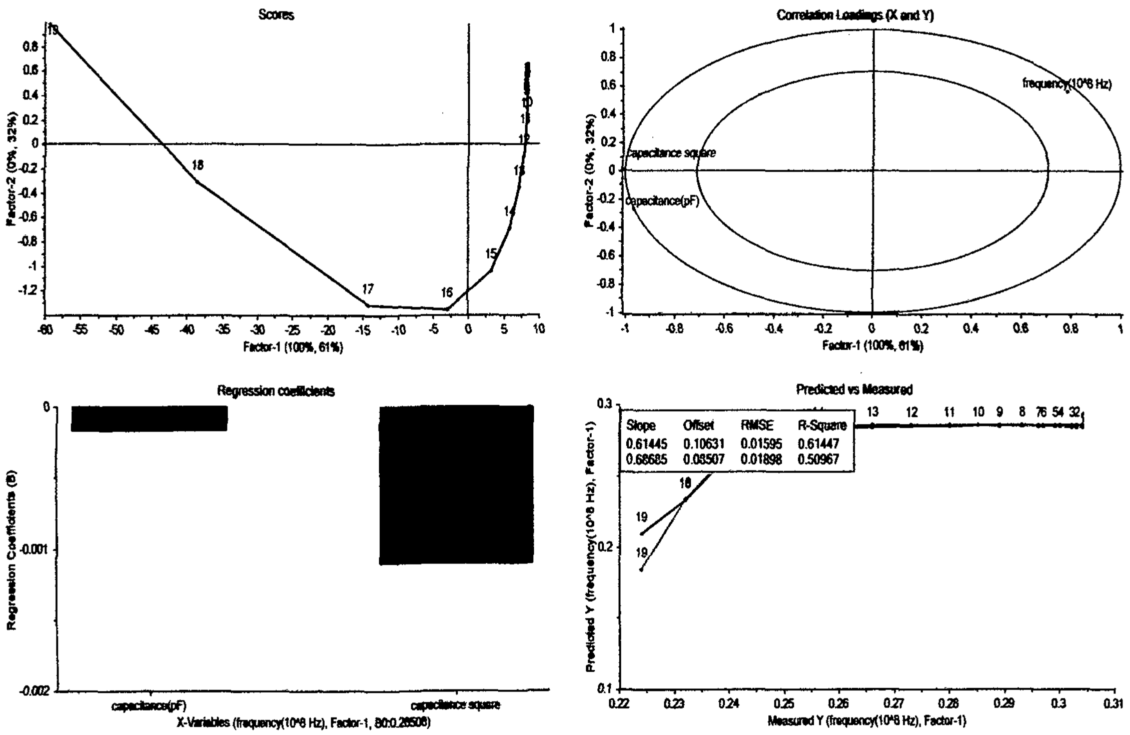


Fig.7.32 Regression between the moisture and capacitance for Factor 1

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the Colpitts oscillator at the frequency of 30.6 MHz is obtained by using Partial Least Squares or Projection to Latent Structures regression method.

1. REGRESSION BETWEEN THE FREQUENCY AND CAPACITANCE FOR FACTOR 1:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 1 shows two outliers 18 and 19 in the samples. These outliers belong to the group of the samples because samples are missing between the group of the samples and outliers.

2. LOADINGS PLOT:-

The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The frequency is on the opposite direction from the centre of the plot and far from the capacitance and capacitance square. The Y-variable shows 61% explained variance along the factor 1 and 32% explained variance along the factor 2. Thus the frequency is highly negatively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are $-1.108*10^{-3}$, $-1.729*10^{-4}$, 0.28508.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are not close to 1 equal to 0.61447 and 0.50967. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.01595 and 0.01898. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 0.10631 and 0.08507. The slopes corresponding to calibration equation and validation of calibration equation are not close to 1 equal to 0.61445 and 0.68685.

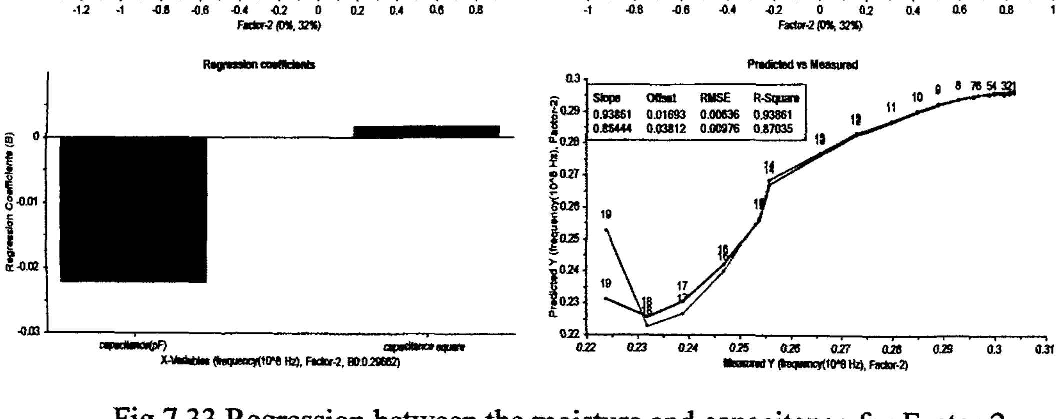


Fig.7.33 Regression between the moisture and capacitance for Factor 2

3. REGRESSION BETWEEN THE FREQUENCY AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

2. SCORES PLOT:-

The scores plot for factor 2 shows one outlier 19 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

5. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are *very close to each other and on the same direction from the centre of the plot.* The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The frequency and capacitance are also on the same direction from the centre of the plot. The frequency and capacitance are in opposite direction from the centre of the plot. The frequency is not close to the capacitance and the capacitance square. The Y-variable shows 61% explained variance along the factor 1 and 32% explained variance along the factor 2. Thus the frequency is not highly positively correlated to the capacitance square but highly negatively correlated to the capacitance for factor 2.

6. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are $-1.753*10^{-3}$, $-2.235*10^{-2}$, 0.29662.

7. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.93861 and 0.87305. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.00636 and 0.00976. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 0.01693 and 0.03812. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.93861 and 0.86444.

The comparison of the regression between the frequency and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the frequency is highly negatively correlated to the capacitance and the capacitance square along the factor 1 but the frequency is not highly negatively correlated to the capacitance square along the factor 2. The frequency is highly negatively correlated to the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the capacitance for the values of the frequency measured. Thus the calibration equation for the Colpitts oscillator at the frequency of 30.6 MHz is

$$F = -1.753*10^{-3}*C^2 - 2.235*10^{-2}*C + 0.29662$$

F = frequency of oscillation (10^8 Hz)

C = capacitance (10^{-10} F)

2. VARIATION OF THE FREQUENCY OF OSCILLATOR WITH CAPACITANCE FOR 61.2 MHz FREQUENCY:-

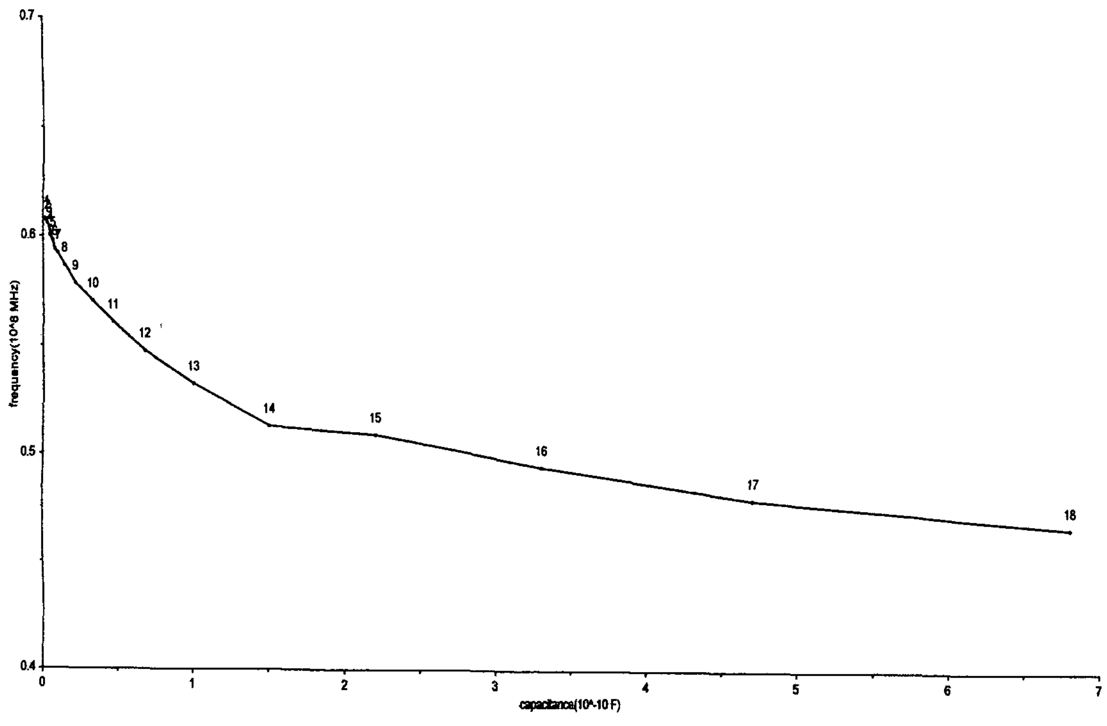


Fig.7.34 Frequency vs capacitance

apacitance (10^{-10} F)	Frequency (10^{8} Hz)	Calibrated frequency (10^{8} Hz)	Error (10^{6} Hz)	Percentage error
0.02	0.60800	0.593982	1.4018	2.30559
0.03	0.60600	0.593475	1.2526	2.06691
0.047	0.60400	0.592614	1.1386	1.88509
0.05	0.60000	0.592463	0.75375	1.25625
0.07	0.59800	0.591455	0.65455	1.09456
0.08	0.59400	0.590952	0.30480	0.513131
0.1	0.59200	0.58995	0.20500	0.34628
0.15	0.58600	0.587463	-0.14625	-0.24957
0.22	0.57800	0.584022	-0.60220	-1.04187
0.33	0.57000	0.578715	-0.87145	-1.52886
0.47	0.56000	0.572135	-1.2134	-2.16687
0.68	0.54700	0.562632	-1.5632	-2.85777
1	0.53200	0.549	-1.7000	-3.19549
1.5	0.51200	0.52975	-1.7750	-3.4668
2.2	0.50800	0.507	0.10000	0.19685
3.3	0.49300	0.48115	1.1850	2.403651
4.7	0.47800	0.46575	1.2250	2.56276
6.8	0.46500	0.4794	-1.4400	-3.09677

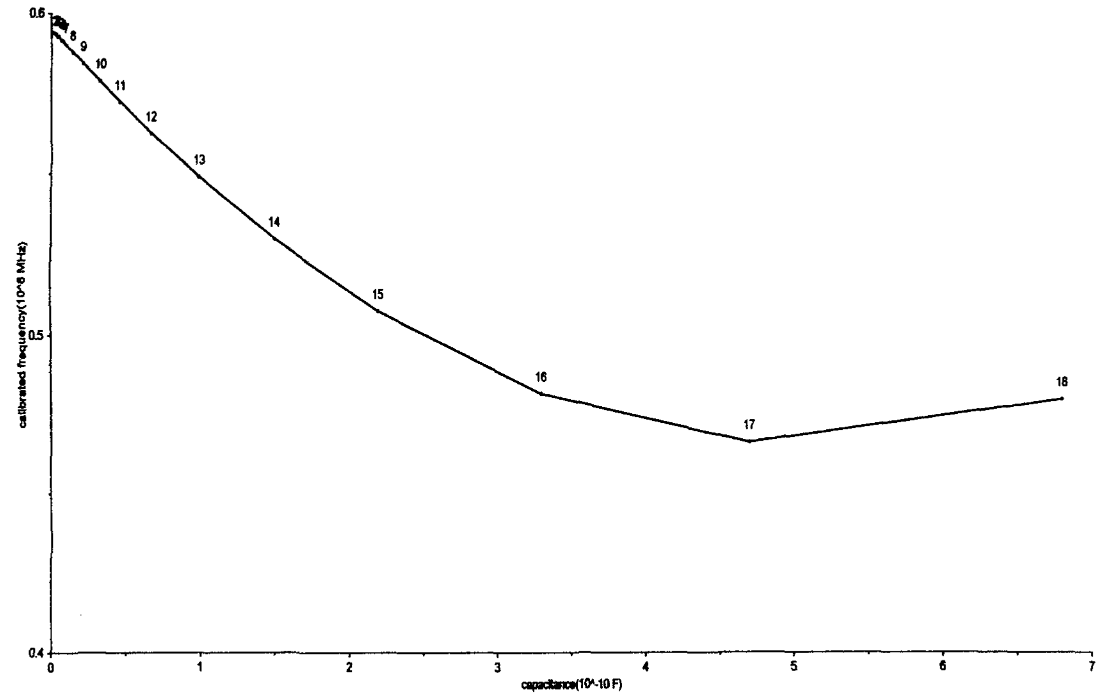


Fig.7.35 Calibrated frequency vs capacitance

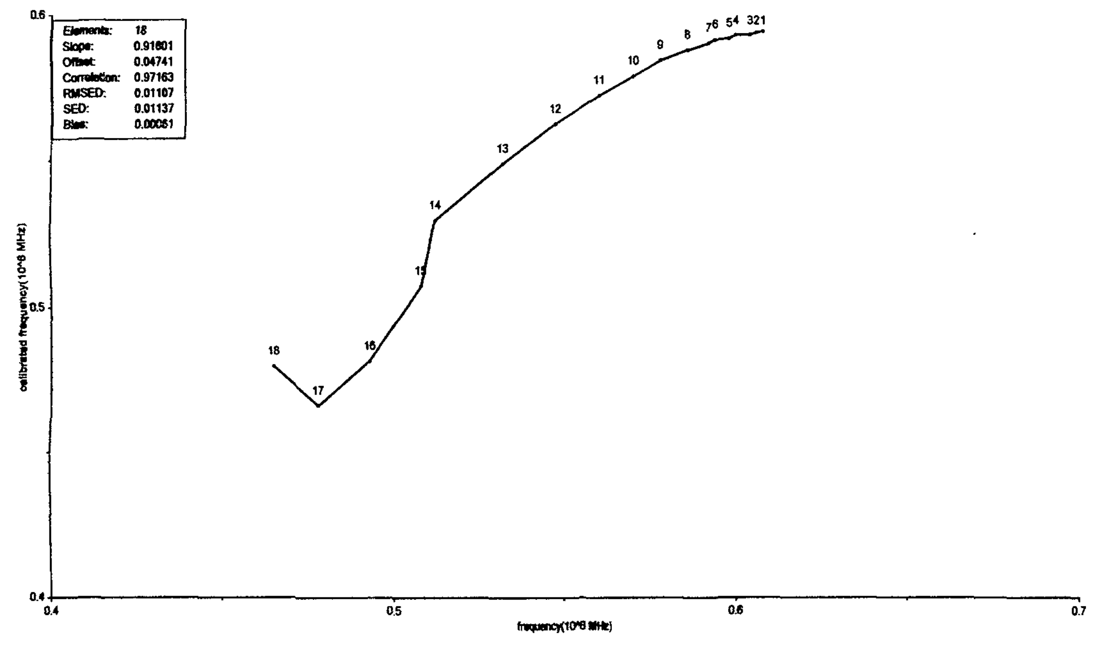


Fig.7.36 Calibrated moisture vs moisture

The graph shows that the correlation coefficient is close to 1 equal to 0.97163. The slope is close to 1 equal to 0.91601. The offset is low equal to 0.04741. The root mean square error of deviation RMSED, the squared error of deviation SED and the bias are close to 0 equal to 0.01107, 0.01137 and 0.00061. Thus the relationship between the calibrated moisture and moisture is highly linear.

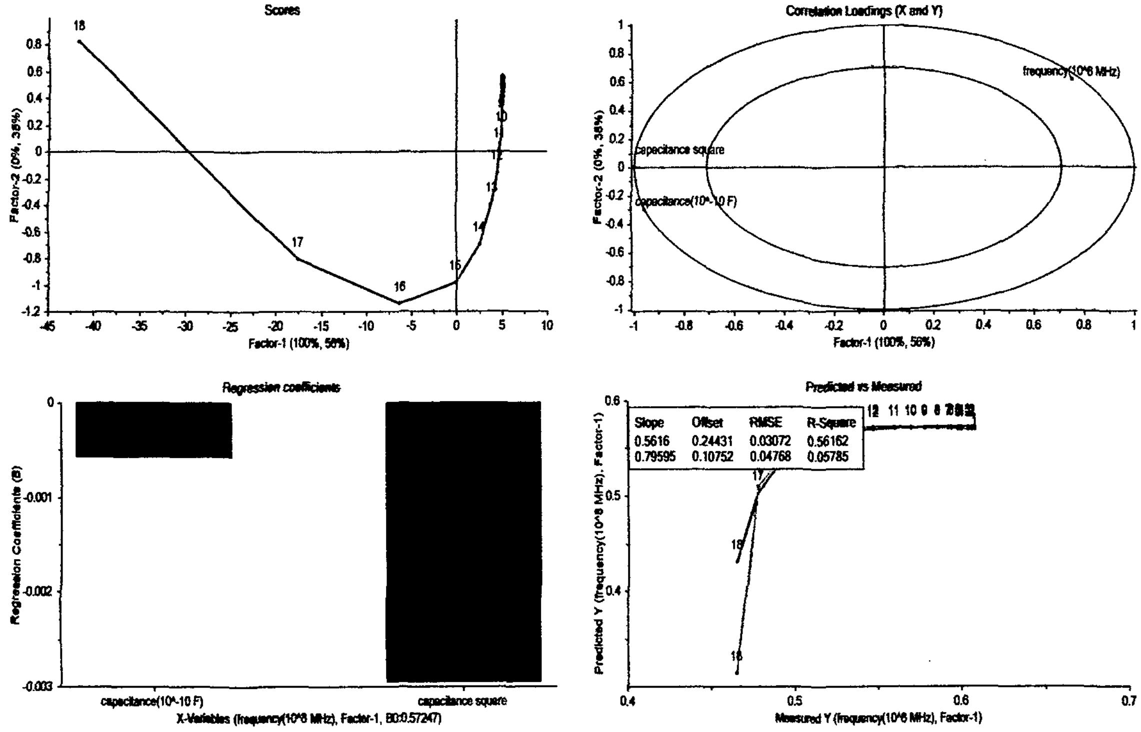


Fig.7.37 Regression between the moisture and capacitance for Factor 1

REGRESSION BETWEEN THE MOISTURE AND CAPACITANCE:-

The calibration equation for the Colpitts oscillator at the frequency of 61.2 MHz is obtained by using Partial Least Squares or Projection to Latent Structures regression method.

2. REGRESSION BETWEEN THE FREQUENCY AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

1. SCORES PLOT:-

The scores plot for factor 1 shows one outlier 18 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

2. LOADINGS PLOT:-

The loadings plot for the factor 1 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 1. The frequency is on the opposite direction from the centre of the plot and far from the capacitance and capacitance square. The Y-variable shows 56% explained variance along the factor 1 and 38% explained variance along the factor 2. Thus the frequency is highly negatively correlated to the capacitance and capacitance square along the factor 1.

3. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 1 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are $-2.958*10^{-3}$, $-5.806*10^{-4}$, 0.57247.

4. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are not close to 1 equal to 0.56162 and 0.05785. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.03072 and 0.04768. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 0.24431 and 0.10752. The slope corresponding to calibration equation is not close to 1 equal to 0.5616. The slope corresponding to validation of the calibration equation is close to 1 equal to 0.79595.

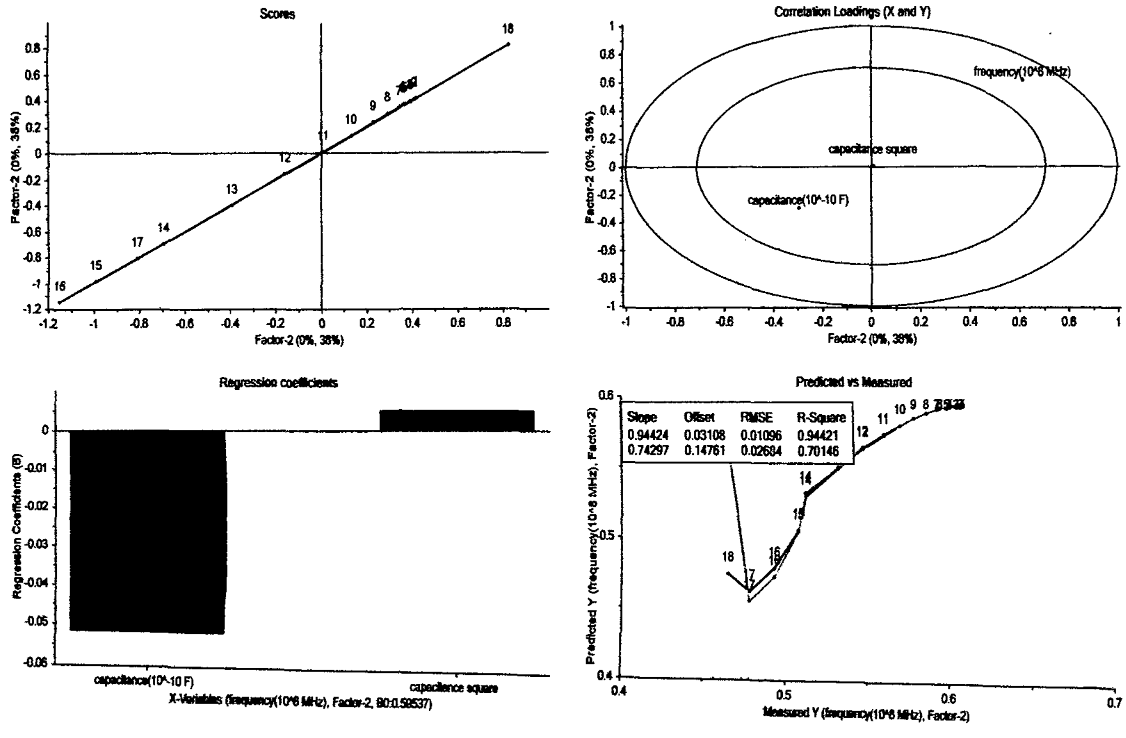


Fig.7.38 Regression between the moisture and capacitance for Factor 2

4. REGRESSION BETWEEN THE FREQUENCY AND CAPACITANCE FOR FACTOR 2:-

The regression graph between the X-variables and Y-variables consists of four plots:-

3. SCORES PLOT:-

The scores plot for factor 2 shows one outlier 18 in the samples. This outlier belongs to the group of the samples because samples are missing between the group of the samples and outlier.

5. LOADINGS PLOT:-

The loadings plot for the factor 2 shows that the capacitance and capacitance square are very close to each other and on the same direction from the centre of the plot. The X-variables show 100% explained variance along the factor 1 and 0% explained variance along the factor 2. Thus the capacitance and capacitance square are highly positively correlated to each other along the factor 2. The frequency and capacitance are also on the same direction from the centre of the plot. The frequency and capacitance are in opposite direction from the centre of the plot. The frequency is not close to the capacitance and the capacitance square. The Y-variable shows 56% explained variance along the factor 1 and 38% explained variance along the factor 2. Thus the frequency is not highly positively correlated to the capacitance square but highly negatively correlated to the capacitance for factor 2.

6. REGRESSION COEFICIENTS PLOT:-

The regression coefficients plot for factor 2 shows that the regression coefficients corresponding to capacitance square, capacitance and constant coefficient are $-5.02*10^{-3}$, $-5.189*10^{-2}$, 0.59537.

7. PREDICTED VS MEASURED PLOT:-

The predicted vs measured plot shows that the correlation coefficients corresponding to calibration equation and validation of the calibration equation are close to 1 equal to 0.94421 and 0.70146. The RMSEC and RMSEP corresponding to calibration equation and validation of calibration equation are close to 0 equal to 0.01096 and 0.02684. The offsets corresponding to calibration equation and validation of calibration equation are low equal to 0.03108 and 0.14761. The slopes corresponding to calibration equation and validation of calibration equation are close to 1 equal to 0.94424 and 0.74297.

The comparison of the regression between the frequency and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the frequency is highly negatively correlated to the capacitance and the capacitance square along the factor 1 but the frequency is not highly negatively correlated to the capacitance square along the factor 2. The frequency is highly negatively correlated to the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the capacitance for the values of the frequency measured. Thus the calibration equation for the Colpitts oscillator at the frequency of 61.2 MHz is

$$F = -5.02*10^{-3}*C^2 - 5.189*10^{-2}*C + 0.59537$$

F = frequency of oscillation (10^8 Hz)

C = capacitance (10^{-10} F)

CHAPTER 8

RESULTS AND CONCLUSIONS

8.1 RESULTS:-

The soil moisture sensor based on FDR technique is designed and developed. The calibration and the testing of the system is done in the various moisture ranges from 0 to 50% and various capacitance ranges from 2 pF to 820 pF. The specifications of the FDR soil moisture sensor system are:-

1. Moisture range – 0 to 50% calibrated and tested, can work upto 100% moisture range.
2. Capacitive probe sensor –
    1. Resolution – 0.66 pF.
    2. Calibration equation for different moisture ranges –
        1. Calibration equation for 0 to 10% moisture range:-
        1. $\theta_v = 6.758*C^2 + 36.78*C + 5.29917$
        2. Sensitivity – 0.3692 %/pF
        3. Error – 1.1714 %
        2. Calibration equation for 10 to 20% moisture range:-
        1. $\theta_v = -1591*C^2 + 476.9*C -22.47842$
        2. Sensitivity – 4.6099 %/pF
        3. Error – 1.2908 %
        3. Calibration equation for 20 to 30% moisture range:-
        1. $\theta_v = 29.49*C^2 + 67.24*C + 10.96639$
        2. Sensitivity – 0.6783 %/pF
        3. Error – 3.5097%
        4. Calibration equation for 30 to 40% moisture range:-
        1. $\theta_v = -1187*C^2 + 882.5*C -127.02523$
        2. Sensitivity – 8.5876 %/pF
        3. Error – 1.631%
        5. Calibration equation for 40 to 50% moisture range:-
        1. $\theta_v = 34.51*C^2 + 41.34*C + 17.97213$
        2. Sensitivity – 0.4203 %/pF
        3. Error – 0.6898%

Colpitts oscillator –

1. Resolution - -0.148 MHz/pF
2. Calibration equation for different frequencies –
    1. Calibration equation for 30.6 MHz frequency:-
    1. $F = -1.753*10^{-3}*C^2 - 2.235*10^{-2}*C + 0.29662$
    2. Sensitivity - $-2.2385*10^{-2}$ MHz/pF
    3. Error – 7.8208%
    2. Calibration equation for 61.2 MHz frequency:-
    1. $F = -5.02*10^{-3}*C^2 - 5.189*10^{-2}*C + 0.59537$
    2. Sensitivity - $-5.199*10^{-2}$ MHz/pF
    3. Error – 1.7908%

8.2 FUTURE SCOPE AND MODIFICATIONS:-

The FDR soil moisture sensor system can be improved by making the following changes in the capacitive probe sensor and the Colpitts oscillator:-

1. The capacitor plates of the capacitive probe sensor can be coated with a thin layer of insulating material which increases the accuracy of the capacitive probe sensor. The length of the capacitor plates can be reduced from 100 mm to 58 mm for the more accurate calibration of the capacitive probe sensor.
2. A band pass filter can be connected at the output of the Colpitts oscillator to pass only the higher 61.2 MHz frequency through it. An amplifier can be connected at the output of the band pass filter to increase the gain of the 61.2 MHz frequency signal.
3. A microcontroller can be connected at the output of the amplifier and programmed to convert the frequency into moisture. A display can be connected at the output of the microcontroller to display the moisture.

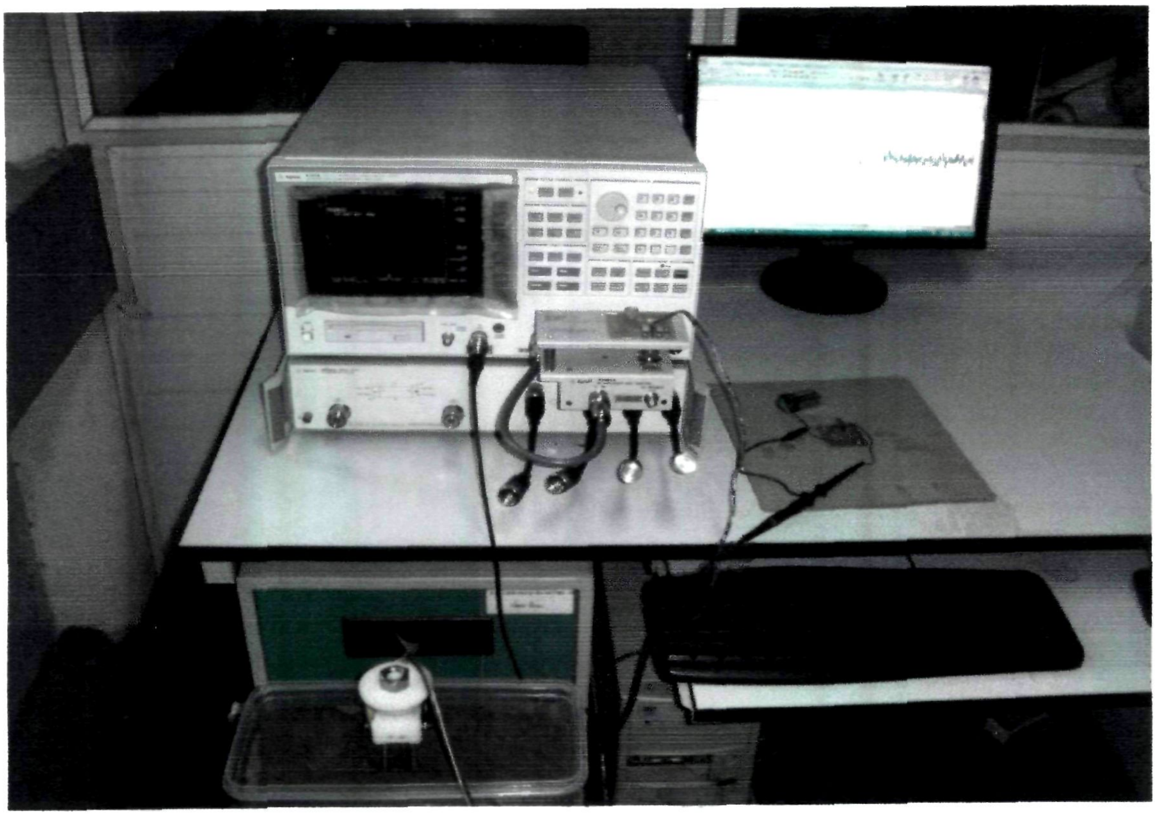


Fig. Complete experimental setup of FDR sensor system

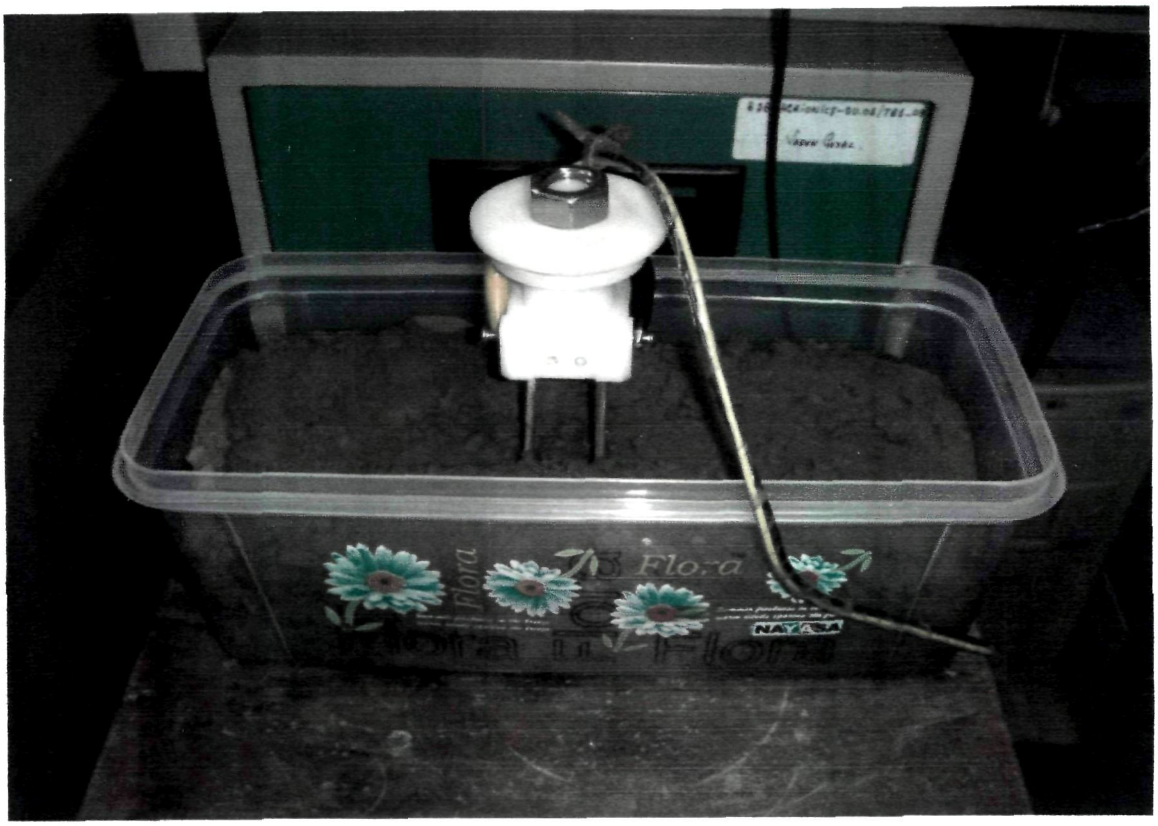


Fig. Capacitive probe sensor

Design of the Capacitive Probe Sensor for the FDR Soil Moisture Sensor System

Baban Kumar, Abhay Gusain*, M.L. Singhla, S.K.Mahna*

Central Scientific Instruments Organisation, (CSIR) Chandigarh

*NIT Kurukshetra, Kurukshetra**

Abstract: **The capacitive probe sensor is a parallel plate capacitor which is used to determine the moisture content of the soil. The probe sensor is connected to an oscillator of the FDR soil moisture sensor system whose output frequency depends upon the capacitance of the probe sensor which in turn depends upon the dielectric constant and thus moisture content of the soil acting as medium between the plates of the probe sensor. The capacitive probe sensor is designed and simulated using the Integrated Electro software in order to determine the effects of the parameters like length, width, thickness and gap between the plates on the parameters like electric field, charge, capacitance, sensitivity and resolution of the probe sensor. The simulation results are used to predict and determine the geometry of the probe sensor, the materials that should be used in making the plates of the probe sensor and coating the plates of the probe sensor for reducing the effects of the fringing field and noise in the environment. The design proposes unique multi-capacitive array geometry to counter the effect of inherent soil heterogeneity, to increase sensing precision, to extract the exact variance responsible for soil moisture variations out of other complex components' such as conductivity which forms an integral part of the complex permittivity matrix of the water molecule existing in the soil volume under measurement and so forth, apart from this the effect of Teflon coating on the outer surfaces of the proposed designed probe has been also simulated to get its resulting field solutions in the simulation software. Various electrical input stimulus in terms of different parametric variations has been also observed in the reported studies in terms of its(probe) resolution power, accuracy, immunity to noise signals and sensitivity performance parameters etc.**

Keywords— **Capacitive probe sensor, Simulation, Parameters effects**

I. INTRODUCTION

The capacitive probe sensor is an important part of the FDR soil moisture sensor system. The parameter used for the measurement of the soil moisture is the capacitance of the probe sensor. The dielectric constant of the soil depends upon the moisture content of the soil and the capacitance of the probe sensor depends upon the dielectric constant of the soil. Thus the soil moisture content can be measured by measuring the capacitance of the probe sensor. Thus the various possible geometries of the probe sensor are simulated in the Integrated Electro software and the effects of the changes in the geometries in the parameters like electric field are studied. The Integrated Electro software is a powerful simulation tool in which the different 3-D geometries of the probe sensor can be designed in equivalent 2-D geometries and the parameters like the length, width and thickness can be varied to study the changes in the electric field and charge of the probe sensor.

II. THEORY OF THE CAPACITIVE PROBE SENSOR

A. [1]*Volumetric soil moisture content:*

Volumetric soil water content (θ_v) is the ratio between the volume of water present in the soil and the total volume of the sample and is therefore expressed as:

$$\theta_v = (\text{volume of water/total volume})$$
$$\theta_v = \theta_g . r_s$$
$$= (V_w/M_s).(M_s/V_s)$$
$$= (V_w/V_s)$$

V_w = Volume of the water in soil
V_s = Total volume of the soil and water
M_s = Mass of the soil
r_g = Bulk density of the soil

[2]A simple dielectric model that describes the soil as a mixture of solids, water, and air is given by:

$$\varepsilon = [(1 - \varphi)\varepsilon_s{}^{\alpha} + \theta\varepsilon_w{}^{\alpha} + (\varphi - \theta)\varepsilon_s{}^{\alpha}]^{1/\alpha}$$

ε_s, ε_w and ε_a are the relative permittivities for solids, water and air, respectively.

The moisture content of the soil is not constant and varies throughout the volume of the soil. [i]The variation of the moisture content in the soil is not in a certain pattern but the moisture is randomly distributed throughout the soil. [ii]Thus there is inherent heterogeneity in the moisture content of the soil and it is very difficult to determine and extract only the moisture specific electrical variations available at the different points of the soil volume out of the heterogeneity consisting of other elements which also gives electrical variations in the overall variations. [iii]The measurement of the soil moisture at different points require a small sensor to detect the moisture at different points but to measure the soil moisture content over a large area it will take a long time because a small sensor is used which covers smaller volumes while detecting the soil moisture content more precisely. Thus, an optimized sensor should be developed, which can measure the variation of the soil moisture content effectively balancing time, precision and area covered.

The designed capacitive probe sensor consists of four parallel plates for precisely measuring the moisture content of the soil. This is done because the variation of the moisture content in the soil is different at various depths and different points in the region between the plates. Thus to measure the variation of the moisture content at various depths four parallel plates are used in perpendicular directions. Thus capacitance of the capacitive probe sensor is measured in two perpendicular directions and the average capacitance is measured. This increases the accuracy of the measurement of the capacitance of the capacitive probe sensor and thus the moisture content of the soil.

II. DESIGN CONFIGURATIONS OF THE PROBE SENSOR

The probe sensor is designed and simulated through the Integrated ELECTRO software. Three design configurations are taken into consideration.

1. Parallel plate capacitor.
2. Concentric cylindrical capacitor.
3. Rod electrode capacitor.

The variation of capacitance, electric field in the region between electrodes, fringing electric field in the region outside and near to the electrodes, resolution, accuracy, compaction of the soil inside the electrodes and compact probe design with variation in the shape and size of the electrodes are analyzed and an optimum design of the probe sensor is obtained from the analysis.

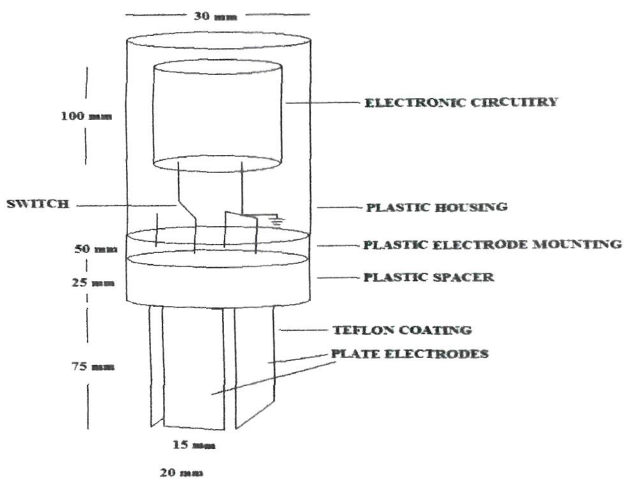


Fig 1: Designed capacitive probe sensor

A. *Parallel plate capacitor:*

A Parallel plate capacitor is designed and simulated in the Integrated Electro software. The dimensions of the capacitor are:-

1. Diameter of electrode – 4 inch.
2. Thickness of the electrode – 0.5 inch.
3. Gap between the electrodes – 0.6 inch.
4. Diameter of the arc of the edge of the electrode – 0.5 inch.

The following parameters are calculated and analysed for the parallel plate capacitor:-

1. *Voltage:*

The two electrodes of the capacitor are given -30V and 30V and the variation of the potential in the region around the electrodes is measured. The potential is maximum at the electrode and decreases with distance away from the electrode.

The electric field in two regions has been taken into consideration.

2. [8]*Electric field in the region between the electrodes:*

The electric field observed in the region between the electrodes is stable, constant and very high i.e. 3.94 kV/m. Thus, a very high, stable and constant electric field in the region between the electrodes increases the accuracy and sensitivity of the proposed capacitive sensor. Because of the high and constant electric field in the region between the electrodes the electric field due to enviromental [15][16][17]noise will disorientate the dipoles less and thus increasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will be changed to the original orientation of the dipoles in the direction of the electric field and thus increasing the sensitivity of the capacitive sensor.

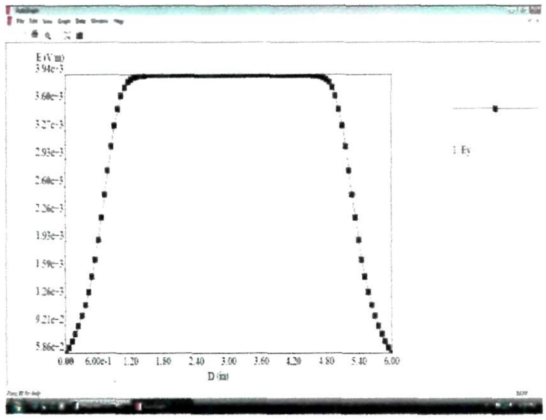


Fig 2. Electric field in the region between the plates for Parallel plate capacitor

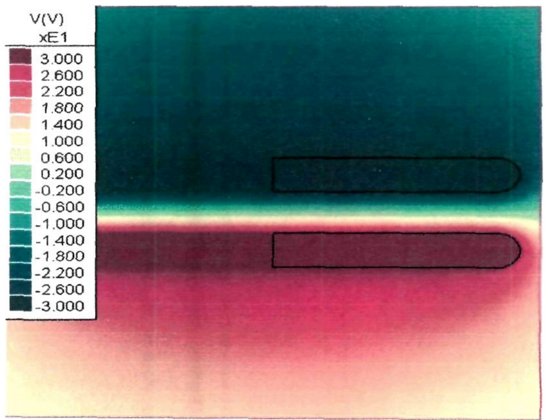


Fig 3. Simulation result for the parallel plate capacitor

3. *Electric field in the region outside and near to the edge of the electrodes :*

The electric field outside and near to edge of the the electrodes is the fringing electric field. This fringing electric field acts as enviromental [15][16][17]noise interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the readings.

The fringing field varies in the range of 3.94 kV/m to 5.86 kV/m when the distance is varied in x-axis between 1.20 inch to 0 inch.

4. *[12][13][14]Capacitance:*

The charge accumulated in each plate of the capacitor is 535.7 pC when the dielectric medium is air. The charge accumulated in the plates changes from 535.7 pC to 890 pC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

5. *[12][13][14]Resolution:*

The minimum charge accumulated on each plate is 535.7 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 8.69 pF. Thus the resolution of the capacitor for the dielectric medium of air is 8.69 pF.

6. *[12][13][14]Sensitivity:*

The sensitivity of the parallel plate capacitor is given by the equation

$$dC/d\varepsilon = \varepsilon_0 A/d$$

ε_0 = permittivity of the air
A = area of the each plate
d = gap between the plates
The sensitivity of the capacitor is 4.464 pF.

7. *Concentric cylindrical capacitor:*

A concentric cylindrical capacitor is designed and simulated in the Integrated Electro software. The dimensions of the capacitor are:-

1. Inner diameter of outer electrode – 2 inch.
2. Outer diameter of inner electrode – 0.8 inch.
3. Thickness of the each electrode – 0.2 inch.
4. Gap between the electrodes – 0.6 inch.
5. Length of each electrode – 2 inch.

The following parameters are calculated and analyzed for the concentric cylindrical capacitor:-

1. *Voltage:*
The voltage is kept same as in the case of parallel plate capacitor.

2. *[8]Electric field in the region between the electrodes:*

The electric field in the region between the electrodes is not stable and constant. The electric field is very small. There are two peaks at which the electric field is 221 nV/m. The electric field between the points 2.6 and 3.4 is constant and small equal to -5.43 pV/m. Thus a very low, and varying electric field in the region between the electrodes decreases the accuracy and sensitivity of the capacitive sensor. Because of the low and varying electric field in the region between the electrodes the electric field due to enviromental [15][16][17]noise will disorientate the dipoles more and thus decreasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will not be changed to the original orientation of the dipoles in the direction of the electric field and thus decreasing the sensitivity of the capacitive sensor.

3. *Electric field in the region outside and near to the edge of the electrodes :*

The electric field outside and near to the edge of the electrodes is the fringing electric field. This fringing electric field acts as enviromental [15][16][17]noise interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the moisture measurement readings.

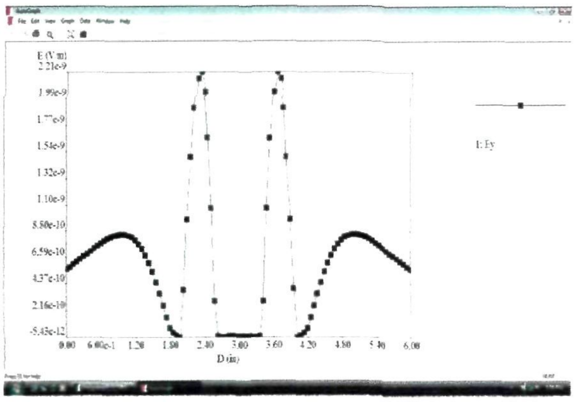


Fig 4. Electric field in the region between the plates for Concentric cylindrical capacitor

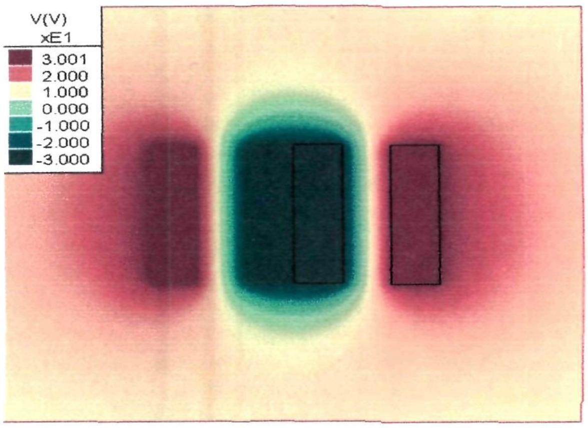


Fig 5. Simulation results for the concentric cylindrical capacitor

The fringing field increases in the range of -5.43 pV/m to 880 pV/m when the distance is varied in x-axis between 2.1 inch to 0.9 inch and then decreases in the range of 880 pV/m to 5.48 pV/m.

4. *[12][13][14]Capacitance:*

The charge accumulated in positive plate of the capacitor is 502.5 pC and in the negative plate is -416.06 pC when the dielectric medium is air. The charge accumulated in the positive plate changes from 502.5 pC to 1.05 nC and in the negative plate changes from -416.06 pC to -976.04 pC when the gap between plates is decreased from 0.6 inch to 0.3 inch.

5. *[12][13][14]Resolution:*

The minimum charge accumulated on each plate is 502.5 pC when the dielectric medium is air at the voltage difference of 60 V. Thus the minimum capacitance of the capacitor is 8.37 pF. Thus the resolution of the capacitor for the dielectric medium of air is 8.37 pF.

6. *[12][13][14]Sensistivity:*

The sensitivity of the concentric cylinder capacitor is given by the equation

$$dC/d\varepsilon = 2\pi\varepsilon_0 l/\log(R1/R2)$$

ε_0 = permittivity of the air

l = length of the each plate

R1 = inner diameter of outer cylinder

R2 = outer diameter of inner cylinder

The sensitivity of the capacitor is 6.054 pF.

8. *Rod electrode capacitor:*

A Rod electrode capacitor is designed and simulated in the Integrated ELECTRO software. A single rod of the capacitor is designed in the Integrated ELECTRO software and results are obtained for it. These results are compared with results obtained for single parallel plate and results are obtained for two rod capacitor by analogy between two results. The dimensions of the capacitor are:-

1. Diameter of the electrode – 0.5 inch.
2. Length of the electrode – 2.5 inch.
3. Length of the cone – 0.5 inch.

The following parameters are calculated and analyzed for the single rod of the rod electrode capacitor and single plate of the parallel plate capacitor:-

1. *Voltage:*

The electrodes of the rod electrode capacitor and parallel plate capacitor are given 30V and the variation of the potential in the region around the electrodes is measured. The potential is maximum at the electrode and decreases with distance away from the electrode.

2. *[8]Electric field in the region between the plates:*

The electric field in the region along the length of the single rod electrode is less stable and constant as compared to the single plate electrode. The electric field for single rod electrode is low as compared to the single plate electrode. the electric field for the single rod electrode decreases from -1.14 kV/m to -1 kV/m between the points 3.15 inch and 4.05 inch and then increases to -1.09 kV/m between the points 4.05 inch and 4.95 inch. The electric field for single plate electrode decreases from -4.64 kV/m to -3.09 kV/m between the points 1.05 inch and 4.95 inch and then increases to -4.64 kV/m. Because the electric field for single rod electrode is less stable, constant and low as compared to the electric field for single plate electrode, the electric field for rod electrode capacitor will be less stable, constant and low as compared to the parallel plate capacitor. Thus, a low, and varying electric field in the region between the electrodes decreases the accuracy and sensitivity of the capacitive sensor. Because of the low and varying electric field in the region between the electrodes, the electric field due to enviromental [15][16][17]noise will disorientate the dipoles more and thus decreasing the accuracy of the capacitive sensor. The small changes in the orientation and number of dipoles due change in the moisture content in the soil will not be changed to the original orientation of the dipoles in the direction of the electric field and thus decreasing the sensitivity of the capacitive sensor.

3. *Electric field in the region outside and near to the edge of the plates:*

The electric field outside and near to the electrodes is the fringing electric field. This fringing electric field acts as enviromental [15][16][17]noise interfering with the connection cables and wires and other components of the sensor and producing a distortion in the output signal and thus producing error in the readings.

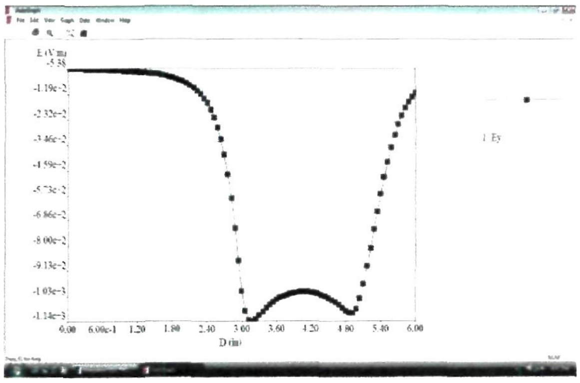


Fig 6. Electric field for the Rod electrode capacitor

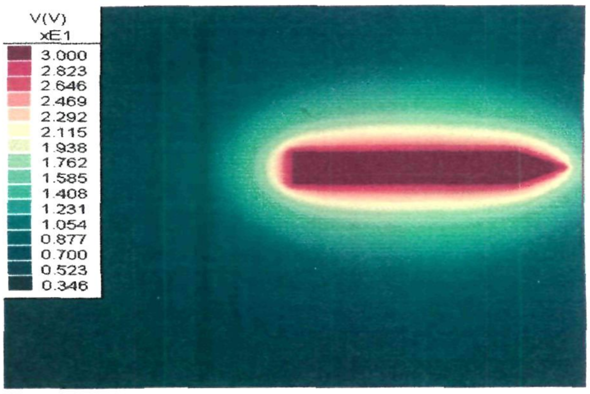


Fig 7. Simulation result for the rod electrode capcitor

The fringing field varies in the range of -1.14 kV/m to -5.38 V/m when the distance is varied in x-axis between 3.15 inch to 0 inch on one side of the rod and -1.09 kV/m to -5.38 V/m when distance is varied in x-axis between 4.95 inch and 8 inch on other side of rod.

4. *[12][13][14]Capacitance:*

The charge accumulated in each plate of the capacitor is 49.32 pC when the dielectric medium is air.

5. *[12][13][14]Resolution:*

The minimum charge accumulated on single rod electrode is 49.32 pC and on the single plate electrode is 13.70 pC, when the dielectric medium is air at the voltage of 30 V. The charge accumulation on each plate of of parallel plate capacitor at a voltage difference of 60V is 535.7 pC and the capacitance is 8.69 pF. The capacitance of the rod electrode capacitor is obtained as 32.14 pF. Thus the resolution of the capacitor for the dielectric medium of air is 32.12 pF.

B. Effects of varying the dimensions of capacitor on parameters:

1. Length:

The electric field in the region between the plates increases on increasing the length of capacitors in all the three configurations. The fringing field decreases and the rate of the change of the fringing field increases. The charge accumulated on the capacitor increases and thus the resolution of the capacitor decreases. The sensitivity in all the three configurations(parallel plate, cylindrical and rod type) increases.

2. Thickness:

The electric field in the region between the plates increases on increasing the thickness of capacitors in all the three configurations. The fringing field decreases and the rate of the change of the fringing field increases. The charge accumulated on the capacitor increases and thus the resolution of the capacitor decreases. The sensitivity in all the three configurations increases.

3. Gap between the plates:

The electric field in the region between the plates decreases on increasing the gap of capacitors in all the three configurations. The fringing field decreases and the rate of the change of the fringing field increases. The charge accumulated on the capacitor decreases and thus the resolution of the capacitor increases. The sensitivity in all the three configurations increases.

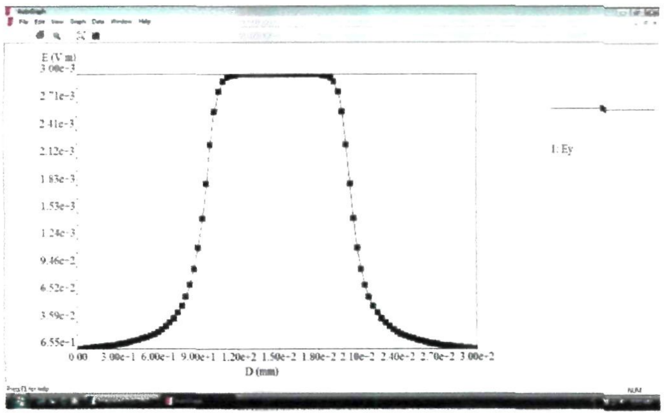


Fig 8: Electric field in the region between the plates

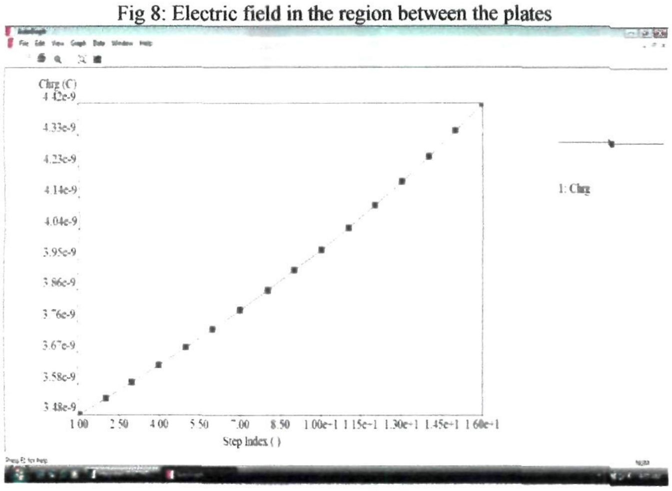


Fig 9: Charge on the positive plate of capacitor

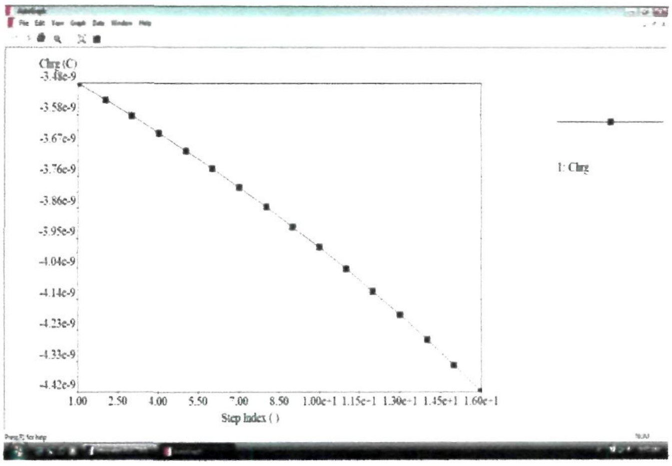


Fig 10. Charge on the negative plate of the capacitor

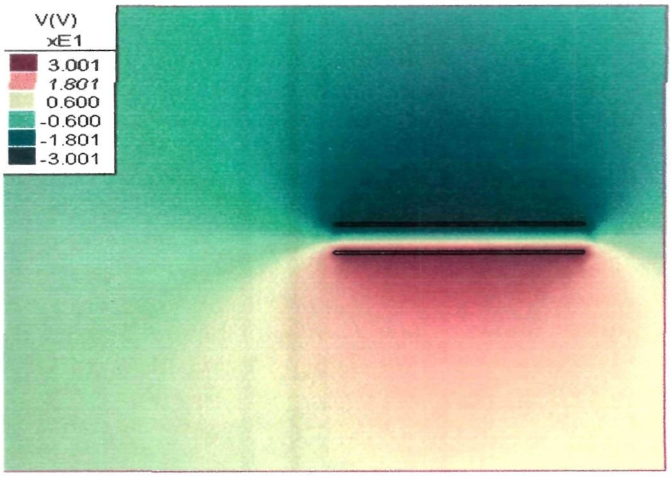


Fig 11. Simulation result for developed parallel plate capacitor

C. Effects of coating materials on the plates of capacitor on parameters:

The outer surface and the edges of the plates of the capacitors are coated with an insulating material with low dielectric constant in order to reduce the effects of the fringing electric field due to the edges of the plates, electric field due to the charge accumulated on the outer surface of the plates, the electric field in the enviroment. The fringing electric field due to the edges of the plates causes induction of charges in the pair of the plates of the second capacitor. This causes an error in the capacitance of the second capacitor. This fringing electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field due to the charge present on the outer surface of the plates causes interference in other nearby components of the sensor. This electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field present in the environment causes an interference with the capacitor. This electric field is reduced by the Teflon coating due to its less dielectric constant.

1. *PROPERTIES OF THE TEFLON:*

The following properties of teflon make it to be used for coating the outer surface of the plates of the parallel plate capacitive sensor.

1. *RESISITANT TO MANY MATERIALS:*

This includes ozone, chlorine, acetic acid, ammonia, sulfuric acid and hydrochloric acid. The only chemicals known to affect these coatings are molten alkali metals and highly reactive fluorinating agents. Thus Teflon will be affected less by the chemicals and ionic solutions present in the soil.

2. *WEATHER AND UV RESISTANCE:-*

The Teflon coated plates will more resistant to weather. Thus the Teflon coated plates have long endurance and durability.

3. *NON STICK:*

Very few solid substances will permanently adhere to a Teflon coating. While tacky materials may show some adhesion, almost all substances release easily. Thus the soil and other chemicals will not be able to adhere to Teflon coated plates.

4. *OUTSTANDING PERFORMANCE AT THE HIGHER TEMPERATURES:*

It can temporarily withstand temperatures of 260C and cryogenic temperatures of -240C and still have the same chemical properties. It has an initial melting point of 342C (+- 10C) and a secondary melting point of 327C (+- 10C). Thus Teflon coated plates will be able to operate at higher temperatures.

5. *LOW COEFFICIENT OF FRICTION:*

It is the ratio of the force required to make two surfaces slide over each other. A low number equals low resistance and smooth operation. This indicates the difficulty in sliding one surface against another. The coefficient of friction is generally in the range of 0.05 to 0.20, depending on the load, sliding speed, and type of Teflon coating used. Thus the Teflon coated plates can be penetrated easily into the soil.

6. *NON WETTING:*

Teflon finishes are both hydrophobic and oleophobic, cleanup is easier and more thorough. Thus the error in the capacitance due to moisture will be less.

7. *EXCEPTIONAL DIELECTRIC PROPERTIES:*

Teflon has a high dielectric strength over many different frequencies, low dissipation factor and high surface resistivity. Dielectric strength is the high voltage that the insulating material can withstand before it breaks down. In addition it has a low dissipation factor; this is the percentage of electrical energy absorbed and lost when current is applied to an insulating material. A low dissipation factor means that the absorbed energy dissipated as heat is low. The high surface resistivity refers to the electrical resistance between opposite edges of an unit square on the surface of an insulating material. The fringing electric field due to the edges of the plates causes induction of charges in the pair of the plates of the second capacitor. This causes an error in the capacitance of the second capacitor. This fringing electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field due to the charge present on the outer surface of the plates causes an interference in other nearby components of the sensor. This electric field is reduced by the Teflon coating due to its less dielectric constant. The electric field present in the enviroment causes an interference with the capacitor. This electric field is reduced by the Teflon coating due to its less dielectric constant.

III. RESULTS

The study of the simulation of the different configurations of the capacitive probe sensor suggests that the parallel plate configuration with following dimensions should be used for the design of the capacitive probe sensor. The parallel plate capacitor has the resolution of 8.69 pF near to the resolution of 8.37 pF of concentric cylindrical capacitor and highest sensitivity of 4.164 pF. The electric field between the electrodes is stable, constant and highest equal to 3.94 kV/m. Though the fringing electric field of parallel plate capacitor is highest equal to 5.86 kV/m but the rate of the change of fringing electric field with distance is also highest - 2.02 kV/m. Thus the parallel plate capacitor is used for making electrodes of the capacitive sensor.

Two parallel plate capacitors are kept perpendicular to each other measuring the soil moisture content in the same volume of the soil. The capacitors are made of aluminium metal. The dimensions of the capacitor are:-

1. Length of the electrode – 100 mm.
2. Width of the electrode – 15 mm.
3. Thickness of the electrode – 1 mm.
4. Gap between the electrodes – 20 mm.

1. Electric field – 3 kV/m.
2. Rate of change of fringing field – 0.066 kV/m.
3. Resolution – 0.87 pF.
4. Sensitivity – 0.17 pF.

The capacitive probe sensor is developed and measurement of the soil moisture is done in five moisture ranges from 0 to 50%. The practical results obtained for the capacitive probe sensor shows that the performance of the developed capacitive probe sensor is close to the performance of the simulated capacitive probe sensor. The following are the specifications of the developed capacitive probe sensor in five moisture ranges:

1. 0 to 10%:
   1. Sensitivity – 0.3692 %/pF
   2. Error – 1.1714 %
2. 10 to 20%:
   1. Sensitivity – 4.6099 %/pF
   2. Error – 1.2908 %
3. 20 to 30%
   1. Sensitivity – 0.6783 %/pF
   2. Error – 3.5097 %
4. 30 to 40%
   1. Sensitivity – 8.5876 %/pF
   2. Error – 1.631 %
5. 40 to 50%
   1. Sensitivity – 0.4203 %/pF
   2. Error – 0.6898 %

Thus the sensitivity of the developed probe sensor ranges from 0.3692 %/pF to 8.5876 %/pF and the error ranges from 0.6898 % to 3.5097 % for the moisture range from 0 to 50%.

IV. CONCLUSIONS AND DISCUSSION

The capacitive probe sensor forms an important part of the FDR soil moisture sensor system and thus parameters of the capacitive probe sensors are also important. The practical results are improved with improved parameters of the capacitive probe sensor. The parameters of the developed capacitive probe sensor are improved through simulation in the Integrated Electro software. The design of the capacitive probe can be further improved through simulation in more powerful software tools and other parametric variations of frequency selectivity, extracting moisture selective electrical variations, effect of ionic conductivity existing in the soil moisture and the input electrical stimulus tunning can be further investigated to develop precise soil moisture predictive models. Thus, a pre-processing such as software simulations to extract selective parameter of interest out of a whole spectrum of electrical variations in the signal because of real world complex parametric events such as investigation of exact volume of water content in a piece of soil under measurement, becomes an easy and preferable solution. The overall exercise and specific parametric analysis resulted in to producing, an improved practical results of the developed capacitive probe sensor.

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Development and Calibration of the Oscillator Circuitry for the FDR Soil Moisture Sensor System

Baban Kumar, Abhay Gusain*, M.L. Singhla, S.K.Mahna*

Central Scientific Instruments Organisation, (CSIR) Chandigarh

*NIT Kurukshetra, Kurukshetra**

Abstract: **The oscillator circuitry is used to produce a sinusoidal signal whose frequency of oscillation depends upon the parameters of the tank circuitry of the oscillator circuitry. The oscillator used in the FDR soil moisture sensor system is the Colpitts oscillator. The output frequency of the Colpitts oscillator depends upon the inductance L and series combination of two capacitances C1 and C2 of the tank circuit of the Colpitts oscillator. The capacitance of the capacitive probe sensor forms the capacitance C1 of the tank circuit of the oscillator. Thus the oscillating frequency of the oscillator varies with variation in the *moisture content of the soil.* The measurement of the soil moisture content is done in two steps. The measurement of the variation of the capacitance of the capacitive probe sensor with variation in the soil moisture and the measurement of the variation of the frequency of oscillation of Colpitts oscillator with variation in the capacitance of the capacitive probe sensor. Thus two calibration equations between the capacitance of the capacitive probe sensor and soil moisture and the frequency of oscillation and the capacitance of the capacitive probe sensor are obtained for the measurement of the soil moisture. The calibration equation between the capacitance of the capacitive probe sensor and soil moisture is obtained for different moisture ranges from 0 to 50%. The calibration equation for the frequency of oscillation and the capacitance of the capacitive probe sensor is obtained by using standard capacitors to increase the accuracy of the measurement.**

Keywords— **Capacitive probe sensor, Oscillator, Frequency of the oscillation, Calibration**

I. INTRODUCTION

The Colpitts oscillator forms an important part of the FDR soil moisture sensor system. The parameter that is used for the measurement of the soil moisture is the frequency of the oscillation of the Colpitts oscillator which depends upon the capacitance of the capacitive probe sensor and thus on the soil moisture content. Thus the Colpitts oscillator is designed through simulation the TINA Pro simulation software and the variation in the output frequency of the oscillator with the variation in the capacitance of the capacitive probe sensor and the effects of the various parameters like the capacitance of the capacitive probe sensor , capacitance of the capacitor of the tank circuit and inductance of the inductor of the tank circuit are studied. The Colpitts oscillator is developed in the hardware and calibration equation between the frequency of the oscillation of the oscillator and the capacitance is obtained.

II. THEORY OF THE COLPITTS OSCILLATOR

A Colpitts oscillator is one of a number of designs for electronic oscillator circuits using the combination of an inductance (L) with a capacitor (C) for frequency determination, thus also called LC oscillator. One of the key features of this type of oscillator is its simplicity (needs only a single inductor) and robustness.

The frequency is generally determined by the inductance and the two capacitors.

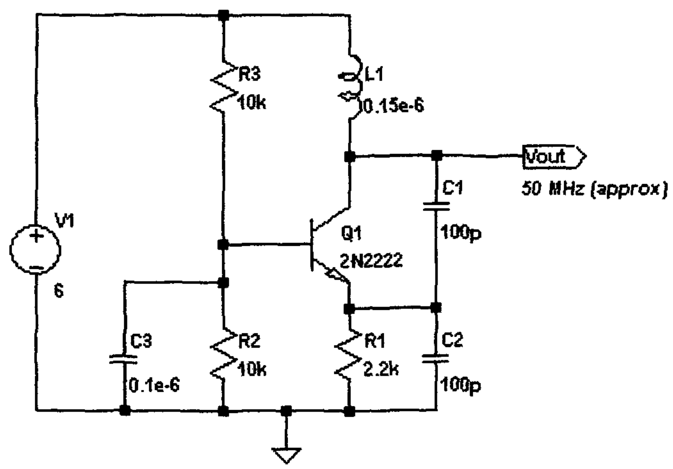

Fig. Practical common base Colpitts oscillator (with an oscillation frequency of ~50 MHz)

III. SIMULATION OF COLPITTS OSCILLATOR FOR ITS EFFECTIVE IMPLEMENTATION

The Colpitts oscillator design used for the sensor implementation works at the frequency of 50MHz while an oscillator that can generate sinusoidal waves of upto 1.024GHz is required initially for sensor implementation. Previously an oscillator that can generate sinusoidal waves upto 1.024 GHz was required. Thus the possibility of the effective implementation of the oscillator for 1.024 GHz in hardware is determined through simulation of the Colpitts oscillator in TINA PRO 7.0 simulation software.

The Colpitts oscillator circuits used above consists of two capacitors- one of constant value 100pf and other, part of capacitive probe sensor, is having value of 0.16pf without any dielectric medium and one inductor of constant value 0.15μH forming an LC tank circuit.

Thus we have

C1=0.16pf

C2=100pf

L=0.15 μH

Thus C is given by,

C=(C1*C2)/(C1+C2)

C=(100*0.16*10^-24)/(100.16*10^-12)

or C=0.16pf

Thus,

f= 1/(2*3.14*(0.16*0.15*10^-18) ½)

or f=1.027GHz

The Colpitts oscillator design used for the sensor implementation works at the frequency of 50MHz while an oscillator that can generate sinusoidal waves of upto 1.024GHz is required initially for sensor implementation. Thus the oscillator design is implemented practically through TINA pro software tool and the oscillator design is simulated in the TINA pro. The output frequency of the oscillator is given by equation

$$f_0 = \frac{1}{2\pi\sqrt{L \cdot \left(\frac{C_1 \cdot C_2}{C_1+C_2}\right)}}$$

where the series combination of C1 and C2 creates the effective capacitance of the LC tank.

Real circuits will oscillate at a slightly lower frequency due to junction capacitances of the transistor and possibly other stray capacitances.

The capacitor C1 is the capacitive sensor used to sense the soil moisture. As C1 is decreased from the value of 100pf to lower values the frequency of oscillation increases from 50MHz to higher values. As the value of the capacitor is decreased to 0.16pf the output frequency of oscillation increases to 1.024GHz. The practical variation of the frequency is measured through the simulation. The simulation results obtained gives the actual variation of the frequency with the capacitance and differences of the actual values from the theoretical values.

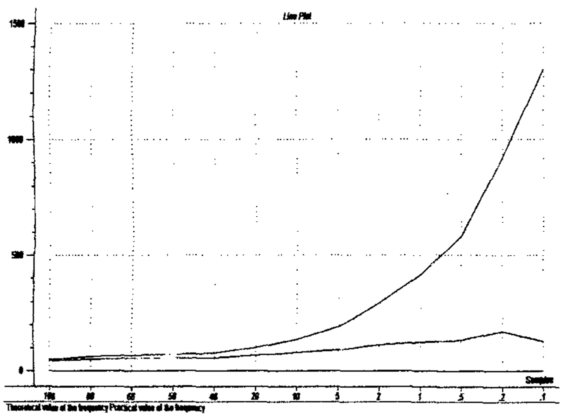

Fig. Frequency vs capacitance for transistor BC547 for frequencies less than 1.024 GHz

The values that are obtained theoretically by the equation for the frequency of oscillation are much different as obtained practically from the simulation. There are two reasons for this variation. The first reason for such variation is the type of the transistor used in the oscillator circuit. The transistor used is BC547. The transistor is changed to QN2222A.

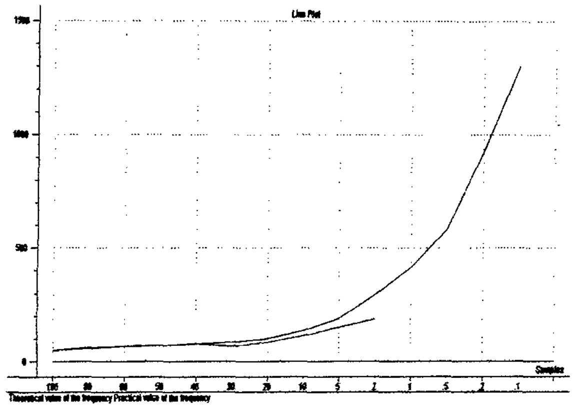

Fig. Frequency vs capacitance for frequencies less than 1.024 GHz for transistor QN2222A

The values of the frequency of oscillation obtained theoretically and practically are still much different. The reason for such variation is the type of transistor. The following transistors are used and the value of frequency of oscillation is obtained at 100pf. The value of the frequency of oscillation obtained is much close to 50MHz so the transistors can be used for implementation of oscillator.

1. MMBT 2369LT1
2. MPQ6700
3. MPS2712
4. MPS3826
5. MPS6544
6. MPS6546
7. MPS6547
8. MPS6548
9. MPS706A
10. MPS8099

The transistor MMBT 2369LT1 is used. The oscillator design is used for frequencies less than 50MHz because the output of the oscillator is stable and close to the theoretical values for frequencies less than 50MHz. Thus the capacitance is increased from 100pf to higher values.

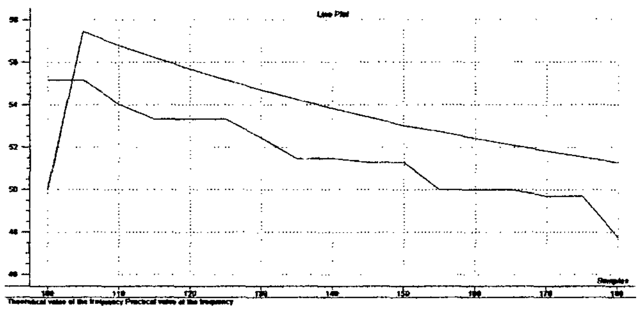

Fig. Frequency vs capacitance for frequencies near to 50 MHz for transistor MMBT 2369lt1

The values of the frequency of oscillation obtained theoretically and practically are not much different with an average error of 2.34 MHz. Thus the oscillator is implemented for frequencies near to 50 MHz.

IV. HARDWARE IMPLEMENTATION AND ANALYSIS OF FDR SENSOR SYSTEM

The FDR sensor system is implemented on hardware and experiments are done on soil samples prepared. The experiments are done in order to determine the calibration equation for the FDR sensor system which gives the relationship between the soil moisture and frequency of the oscillator. After the determination of the calibration equation the testing of the FDR sensor system can be done on soil samples prepared and the accuracy of the FDR sensor system can be determined after comparison with standard soil moisture sensor.

The ·experiments consist of preparation of soil samples, measurement of the capacitance and frequency of the FDR sensor system for the given soil moisture using the Agilent4396B impedance/spectrum analyzer, measurement of the soil moisture of the given samples using POGO soil moisture sensor and interfacing of the impedance/spectrum analyzer and computer for recording and analyzing the data.

A sample of soil is prepared in a container. The soil is kept fine with less number of rocks, organic material and other materials in it. The soil moisture at different regions of the container is kept different in order to do experiments in these different regions. The Agilent4369B impedance/spectrum analyzer is made to operate in impedance mode. An RF frequency sweep of 100kHz to 1.8GHz is applied across the standard capacitance for the calibration of the impedance/spectrum analyzer. The IF bandwidth is kept 10kHz. The capacitance of the connection cables connecting the capacitive probe sensor to impedance/spectrum analyzer is measured for the compensation from the total capacitance measured by the impedance/spectrum analyzer. The capacitive probe sensor is dipped into the soil at certain region of the container and capacitance of the capacitive sensor is measured and recorded on the computer. The soil moisture of that region is then measured by the POGO soil moisture sensor. The measurement of the capacitance is done in various regions of the container. The Agilent4369B impedance/spectrum analyzer is made to operate in spectrum mode. The capacitive sensor is connected to the Colpitts oscillator which is connected to the impedance/spectrum analyzer. The frequency of the oscillator is measured for the same regions of the container. The experiment is again done in the intervals of one hour on order to measure the different moisture of the same region at different times. Thus the soil moisture, capacitance and frequency of the oscillator is measured and recorded on the computer. This data is analyzed to obtain the calibration equation of the FDR sensor system.

The soil samples on which the measurement of the soil moisture is done are prepared into five different ranges of the moisture content:-

1. 0 to 10%
2. 10 to 20%
3. 20 to 30%
4. 30 to 40%
5. 40 to 50%

The soil samples are not prepared for the range above than 50% because the soil samples become very wet and diluted for the range above than 50% making the preparation of the soil samples and measurement of the moisture content in soil samples very difficult.

The soil samples on which the measurement of the soil moisture is done are prepared into different ranges of the soil moisture content because different calibration equations are obtained for different ranges which increases the accuracy of the soil moisture sensor. The calibration equation obtained for a whole range of the soil moisture content from 0 to 50% may decrease the accuracy of the soil moisture sensor during the regression of the data obtained for the soil moisture sensor in the range of 0 to 50% thus the whole range of the soil moisture content is divided into different ranges.

1. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 0 TO 10%:-

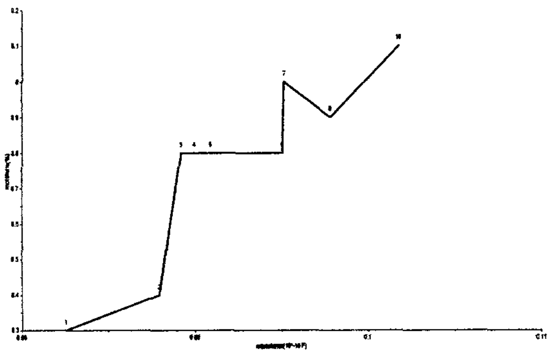

Fig. Moisture vs capacitance

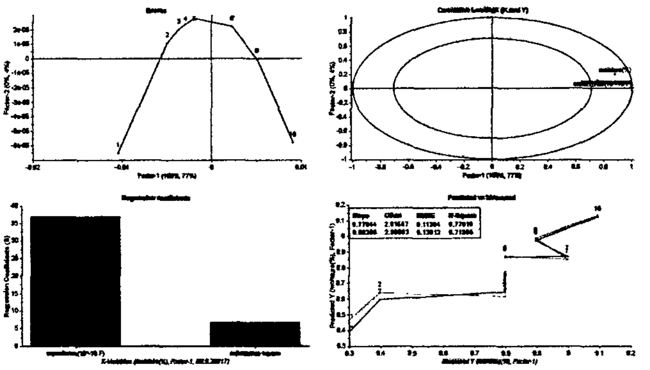

Fig. Regression between the moisture and capacitance for Factor 1

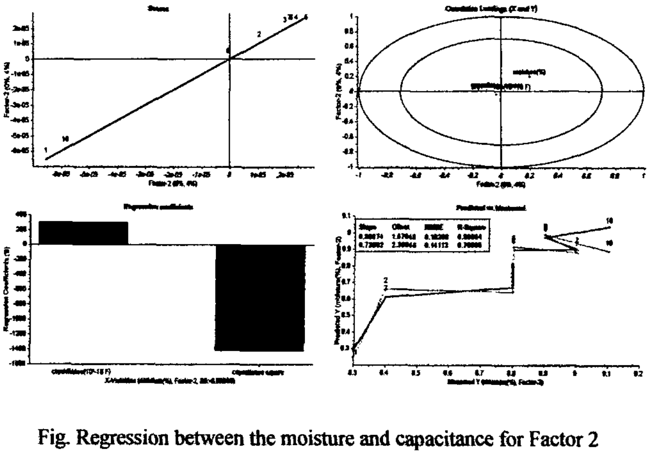

Fig. Regression between the moisture and capacitance for Factor 2

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation are comparable and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 1 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 0 to 10% moisture content is

$\theta_v = 6.758*C^2 + 36.78*C + 5.29917$

θ_v = moisture (%)

C = capacitance (10^{-10} Hz)

2. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 10 TO 20%:-

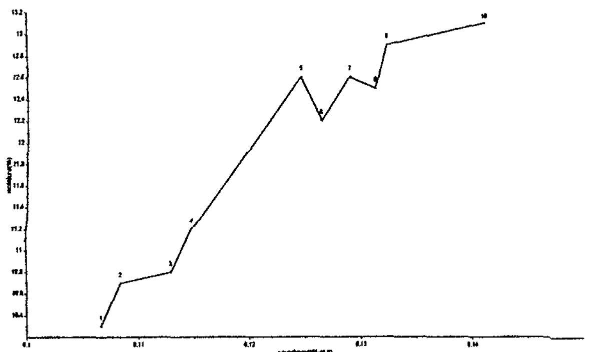

Fig. Moisture vs capacitance

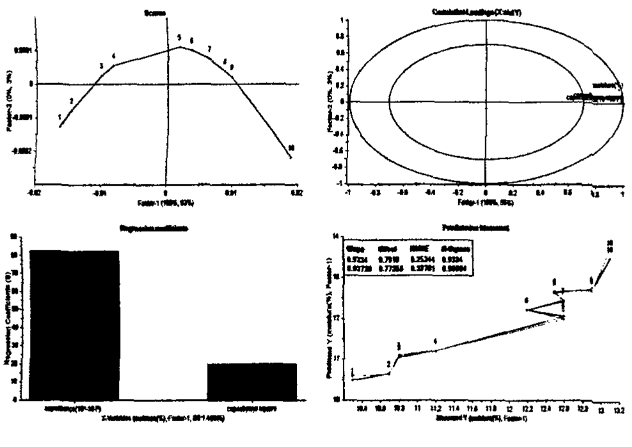

Fig. Regression between the moisture and capacitance for Factor 1

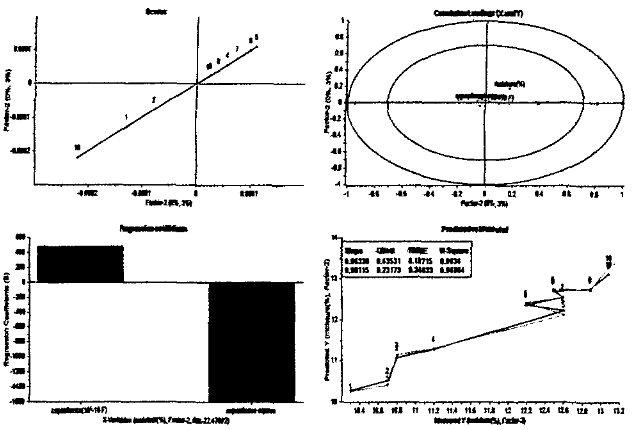

Fig. Regression between the moisture and capacitance for Factor 2

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 10 to 20% moisture content is

$\theta_v = -1591*C^2 + 476.9*C - 22.47842$

θ_v = moisture (%)

C = capacitance (10^{-10} Hz)

3. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 20 TO 30%:-

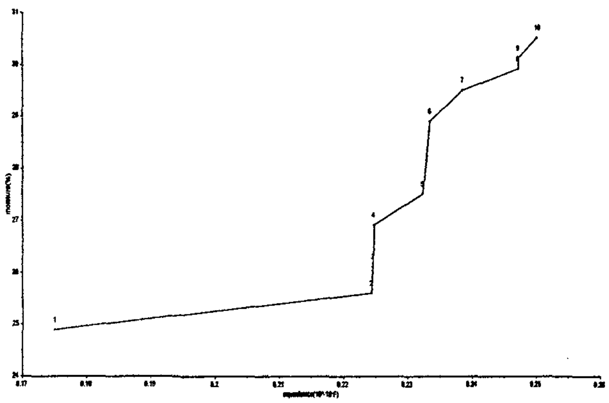

Fig. Moisture vs capacitance

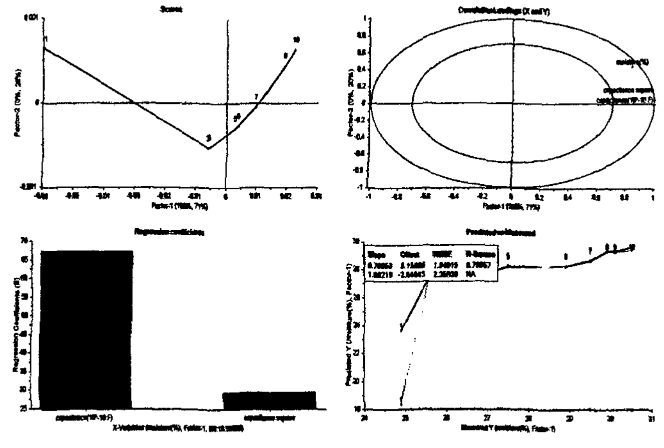

Fig. Regression between the moisture and capacitance for Factor 1

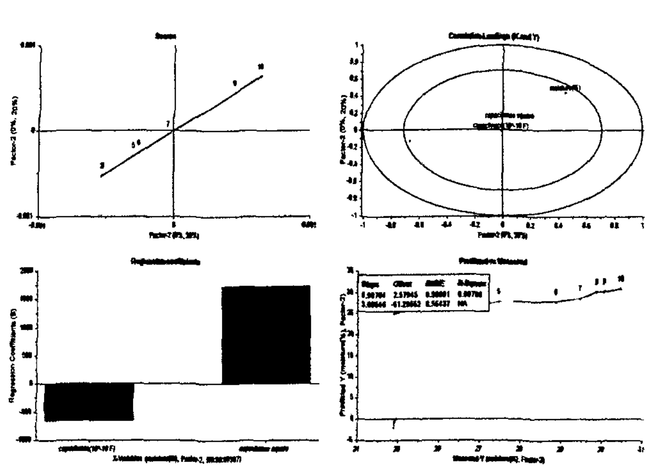

Fig. Regression between the moisture and capacitance for Factor 2

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 1 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 20 to 30% moisture content is

$$\theta_v = 29.49*C^2 + 67.24*C + 10.96639$$

θ_v = moisture (%)

C = capacitance (10^{-10} Hz)

4. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 30 TO 40%:-

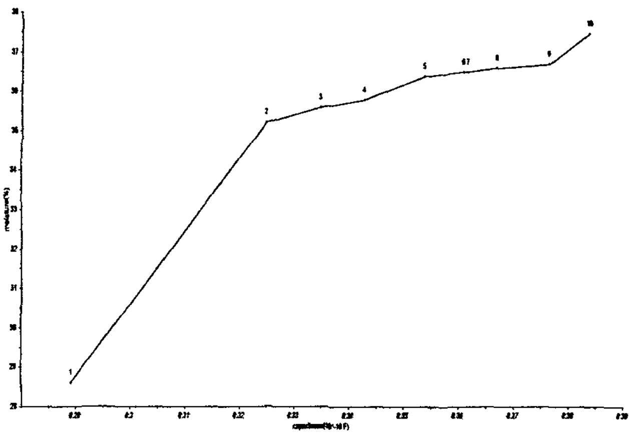

Fig. Moisture vs capacitance

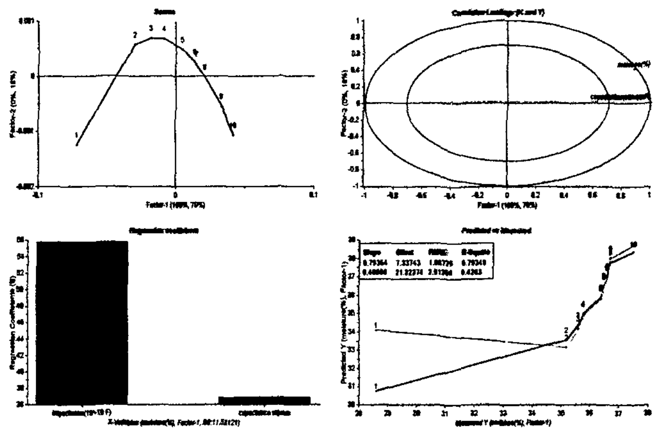

Fig. Regression between the moisture and capacitance for Factor 1

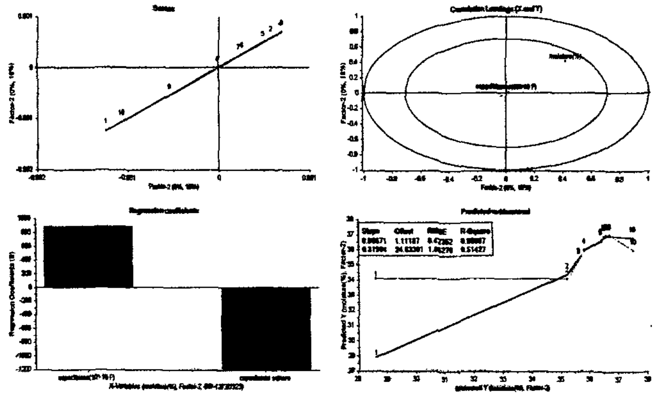

Fig. Regression between the moisture and capacitance for Factor 2

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 30 to 40% moisture content is

$\theta_v = -1187*C^2 + 882.5*C - 127.02523$

θ_v = moisture (%)

C = capacitance (10^{-10} Hz)

5. VARIATION OF THE CAPACITANCE OF THE CAPACITIVE SENSOR WITH SOIL MOISTURE FOR THE RANGE OF 40 TO 50%:-

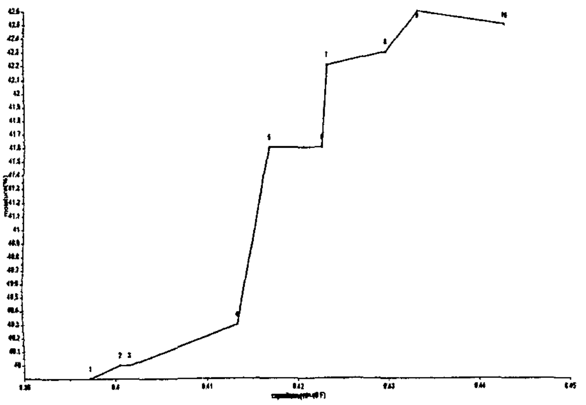

Fig. Moisture vs capacitance

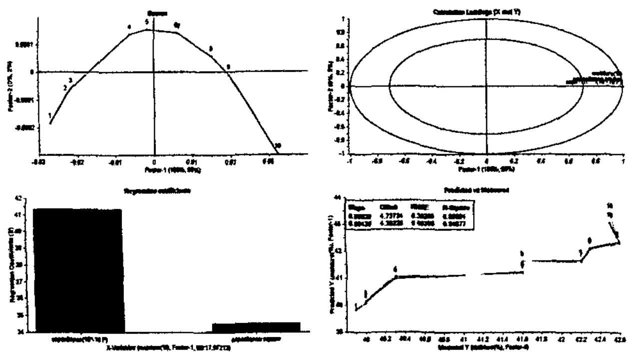

Fig. Regression between the moisture and capacitance for Factor 1

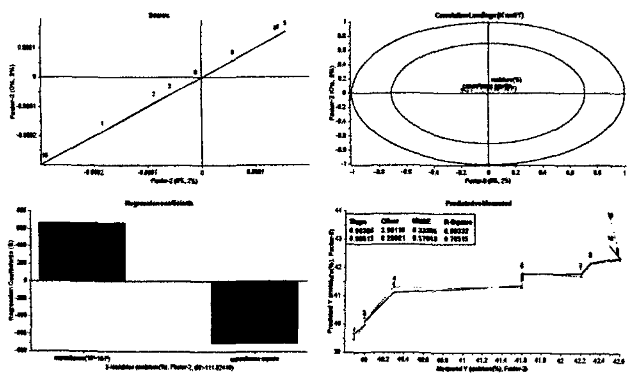

Fig. Regression between the moisture and capacitance for Factor 2

The comparison of the regression between the moisture and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation are comparable and the moisture is highly positively correlated to the capacitance and the capacitance square along the factor 1 but the moisture is not highly positively correlated to the capacitance square and the capacitance along the factor 2. Thus the calibration equation for the factor 1 should be used to predict the values of the moisture for the values of the capacitance measured. Thus the calibration equation for the range of 40 to 50% moisture content is

$\theta_v = 34.51*C^2 + 41.34*C + 17.97213$

θ_v = moisture (%)

C = capacitance (10^{-10} Hz)

V. VARIATION OF THE FREQUENCY OF OSCILLATOR WITH CAPACITANCE OF THE CAPACITIVE PROBE SENSOR:-

The variation of the frequency of the oscillation of the Colpitts oscillator with the variation in the capacitance of the capacitive probe sensor is measured by the impedance/spectrum analyzer. The calibration equation for the Colpitts oscillator is determined by connecting the various standard capacitors in the range from 2 pF to 820 pF across the 100 pF capacitor C2 of the Colpitts oscillator. The output of the Colpitts oscillator is connected to the 50Ω S input of the impedance/spectrum analyzer. The impedance/spectrum analyzer is used in the spectrum mode to determine the output frequency of the Colpitts oscillator. When no capacitor is connected across the 100 pF capacitor C2 the impedance/spectrum analyzer shows two peaks 30.6 MHz at -21.337 dB gain and 61.2 MHz at -42.674 dB gain. The frequency 61.2 MHz is a harmonic frequency of the frequency 30.6 MHz of the Colpitts oscillator. When the capacitors are connected across the 100 pF capacitor C2 the frequency of the oscillation of the Colpitts oscillator decreases from 30.6 MHz and 61.2 MHz to lower values. Thus the measurement of the variation in the frequency of oscillation with variation in capacitance is done at both the frequencies 30.6 MHz and 61.2 MHz.

1. VARIATION OF THE FREQUENCY OF OSCILLATOR WITH CAPACITANCE FOR 30.6 MHz FREQUENCY:-

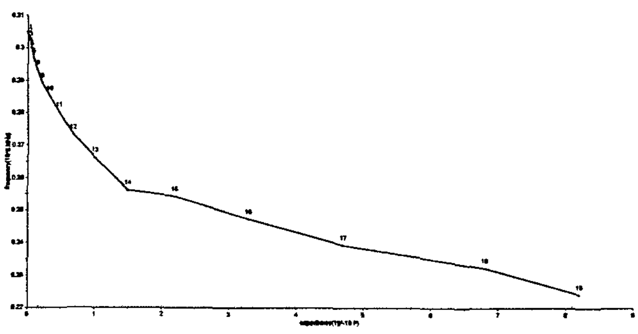

Fig. Frequency vs capacitance

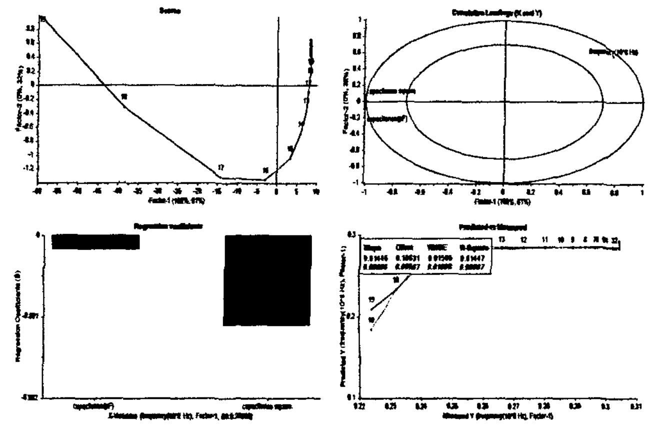

Fig. Regression between the moisture and capacitance for Factor 1

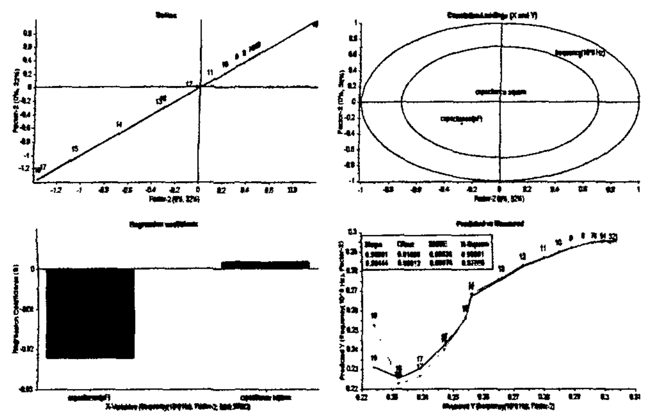

Fig. Regression between the moisture and capacitance for Factor 2

The comparison of the regression between the frequency and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the frequency is highly negatively correlated to the capacitance and the capacitance square along the factor 1 but the frequency is not highly negatively correlated to the capacitance square along the factor 2. The frequency is highly negatively correlated to the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the capacitance for the values of the frequency measured. Thus the calibration equation for the Colpitts oscillator at the frequency of 30.6 MHz is

$$F = -1.753*10^{-3}*C^2 - 2.235*10^{-2}*C + 0.29662$$

F = frequency of oscillation (10^8 Hz)

C = capacitance (10^{-10} F)

2. VARIATION OF THE FREQUENCY OF OSCILLATOR WITH CAPACITANCE FOR 61.2 MHz FREQUENCY:-

The comparison of the regression between the frequency and the capacitance for factor 1 and factor 2 shows that the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the

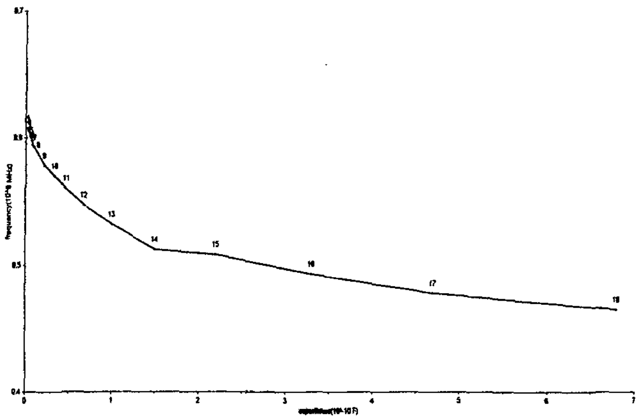

Fig. Frequency vs capacitance

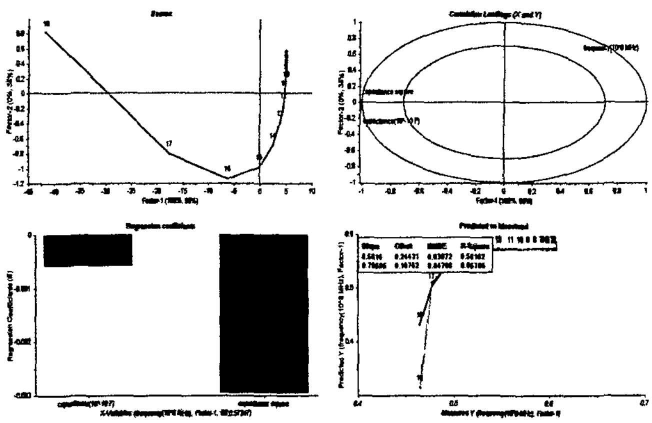

Fig. Regression between the moisture and capacitance for Factor 1

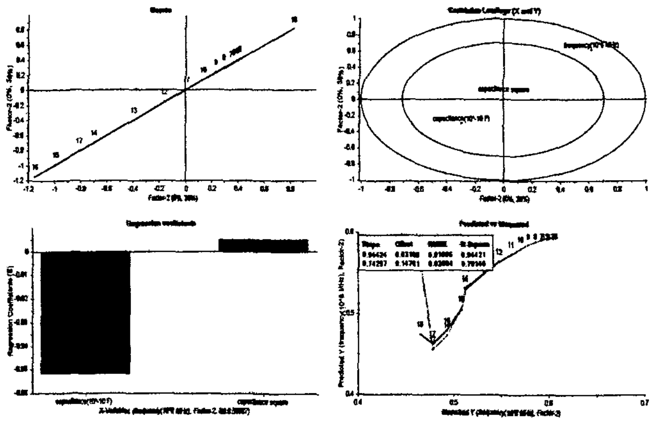

Fig. Regression between the moisture and capacitance for Factor 2

calibration equation and validation of the calibration of the calibration equation for the factor 2 are better as compared to the correlation coefficients, the RMSEC and RMSEP, the offsets and the slopes of regression line corresponding to the calibration equation and validation of the calibration of the calibration equation for the factor 1 and the frequency is highly negatively correlated to the capacitance and the capacitance square along the factor 1 but the frequency is not highly negatively correlated to the capacitance square along the factor 2. The frequency is highly negatively correlated to the capacitance along the factor 2. Thus the calibration equation for the factor 2 should be used to predict the values of the capacitance for the values of the frequency measured. Thus the calibration equation for the Colpitts oscillator at the frequency of 61.2 MHz is

$F = -5.02*10^{-3}*C^2 - 5.189*10^{-2}*C + 0.59537$

F = frequency of oscillation (10^8 Hz)

C = capacitance (10^{-10} F)

IV. CONCLUSIONS AND DISCUSSION

The soil moisture sensor based on FDR technique is designed and developed. The calibration and the testing of the system is done in the various moisture ranges from 0 to 50% and various capacitance ranges from 2 pF to 820 pF. The specifications of the FDR soil moisture sensor system are:-

1. Moisture range – 0 to 50% calibrated and tested, can work upto 100% moisture range.
2. Capacitive probe sensor –
    1. Resolution – 0.66 pF.
    2. Calibration equation for different moisture ranges –
        1. Calibration equation for 0 to 10% moisture range:-
            1. $\theta_v = 6.758*C^2 + 36.78*C + 5.29917$
            2. Sensitivity – 0.3692 %/pF
            3. Error – 1.1714 %
        2. Calibration equation for 10 to 20% moisture range:-
            1. $\theta_v = -1591*C^2 + 476.9*C -22.47842$
            2. Sensitivity – 4.6099 %/pF
            3. Error – 1.2908 %
        3. Calibration equation for 20 to 30% moisture range:-
            1. $\theta_v = 29.49*C^2 + 67.24*C + 10.96639$
            2. Sensitivity – 0.6783 %/pF
            3. Error – 3.5097%
        4. Calibration equation for 30 to 40% moisture range:-
            1. $\theta_v = -1187*C^2 + 882.5*C -127.02523$
            2. Sensitivity – 8.5876 %/pF
            3. Error – 1.631%
        5. Calibration equation for 40 to 50% moisture range:-
            1. $\theta_v = 34.51*C^2 + 41.34*C + 17.97213$
            2. Sensitivity – 0.4203 %/pF
            3. Error – 0.6898%

Colpitts oscillator –

1. Resolution - -0.148 MHz/pF
2. Calibration equation for different frequencies –
    1. Calibration equation for 30.6 MHz frequency:-
        1. $F = -1.753*10^{-3}*C^2 - 2.235*10^{-2}*C + 0.29662$
        2. Sensitivity - -2.2385*10^{-2} MHz/pF
        3. Error – 7.8208%
    2. Calibration equation for 61.2 MHz frequency:-
        1. $F = -5.02*10^{-3}*C^2 - 5.189*10^{-2}*C + 0.59537$
        2. Sensitivity - -5.199*10^{-2} MHz/pF
        3. Error – 1.7908%

FUTURE SCOPE AND MODIFICATIONS:-

The FDR soil moisture sensor system can be improved by making the following changes in the capacitive probe sensor and the Colpitts oscillator:-

1. The capacitor plates of the capacitive probe sensor can be coated with a thin layer of insulating material which increases the accuracy of the capacitive probe sensor. The length of the capacitor plates can be reduced from 100 mm to 58 mm for the more accurate calibration of the capacitive probe sensor.
2. A band pass filter can be connected at the output of the Colpitts oscillator to pass only the higher 61.2 MHz frequency through it. An amplifier can be connected at the output of the band pass filter to increase the gain of the 61.2 MHz frequency signal.
3. A microcontroller can be connected at the output of the amplifier and programmed to convert the frequency into moisture. A display can be connected at the output of the microcontroller to display the moisture.

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