CORROSION RATE SENSOR
BASED ON ELECTROMAGNETICALLY INDUCED CURRENT

By

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Final Draft Report submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

December 2009

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
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December 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mansoor Hussain Khokhar

ABSTRACT

This Report summarizes the research study conducted on the design of corrosion rate sensor based on electromagnetically induced current. This sensor will help in the monitoring the corrosion rate in industries. This inspection system will result in the improvement of safety, environment protection, equipment protection, smooth plant operation and production rate, product quality, profit optimization, monitoring and diagnosis. The design of sensor base on the electromagnetic field to measure corrosion rate, where current is allowed to flow through the metal plate. The current has its own magnetic field around metal plate and if a conducting loop is placed and moved near the magnetic flux, electromagnetically induced current will flow in the conducting loop. The magnitude of electromagnetically induced current should be proportional to the thickness of the metal plate, and the electromagnetically induced current should be lower if the loop is near a corroded region of the metal structure.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my deepest gratitude to Allah the Almighty for the courage to put my plucky efforts in the Final Year Project. I would like to thank to following individuals or groups for giving me moral support through out the semester.

- Dr. Zainal Arif Burhanudin (Final Year Project Supervisor)
- Final Year project Committee
- Resource Center of University Technology PETRONAS
- Mr. Yaseen (Laboratory Assistant)
- University Technology PETRONAS lecturers.

I would like to thank my friends who have morally supported me and my family who encouraged me through out my academic studies.

Lastly I would like to thank all those who were involved directly or indirectly throughout this Final Year Project and in completing this final report. Thanks for your kindness and may Allah bless you all.

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CHAPTER 1

INTRODUCTION

The main objective of this chapter is to provide a clear view of what the project is all about, and outlines has to be done to fulfill the identified needs. The introduction of report includes the background of study, its objectives, problem statement and scope of study.

1.1 Background of Study

Being an engineer when we use to have a discussion about the industries, we take into consideration few concepts in our mind such as Safety, Environmental protection, Equipment protection, Smooth plant operation and production rate, product quality, Profit optimization, Monitoring and diagnosis. In order to meet these process objectives, several control strategies and diagnosis techniques are applied in the industries.

Degradation of pipeline (Corrosion) is also a major issue in the industries, causing explosion of pipeline resulting the bad affect on plant performance. This mainframe of this work is to design and manufacture the corrosion rate sensor based on electromagnetically induced current. Corrosion of steel structures and pipeline may have cost severe environmental and economical damage if left unmonitored. In 1967, Silver Bridge collapsed into the Ohio River after crack grows via corrosion fatigue. More recently, in October 2008, a gas pipeline carrying pressurized natural gas in Prudhoe Bay, Alaska burst with corrosion suspected as the main cause of failure. [1]

This sensor is based on electromagnetic induced current to measure corrosion rate. Essentially, current will be allowed to flow through the metal plate. The current has its own magnetic field and if a conducting loop is placed and moved near the magnetic flux, electromagnetically induced current will flow in the conducting loop. The magnitude of electromagnetically induced current should be proportional to the thickness of the metal plate and the induced current should be lower if the loop is near a corroded region of the metal plate.

1.2 Problem Statement

In a modern business environment, successful enterprises cannot tolerate major corrosion failures, especially those involving personal injuries, fatalities, unscheduled shutdowns and environmental contamination. For this reason considerable efforts are generally expended in corrosion control at the design stage and in the operational phase.

Corrosion can lead to failures in plant infrastructure and machines that are usually costly to repair, costly in terms of lost or contaminated product, in terms of environmental damage, and possibly costly in terms of human safety. Decisions regarding the future integrity of a structure or its components depend on an accurate assessment of the conditions affecting its corrosion and rate of deterioration. With this information an informed decision can be made as to the type, cost and urgency of possible remedial measures [2].

Required levels of maintenance can vary greatly depending on the severity of the operating environments. While some of the infrastructure equipment might only require regular repainting and occasional inspection of electrical and plumbing lines, some chemical processing plants, power generation plants, aircraft and marine equipment, are operated with extensive maintenance schedules.

1.2 Objectives of the study

To design a corrosion rate sensor, that Measures data of corroded & good metal plate using the proposed method.

- ✓ To induce the electromagnetic field in metal plate.
- ✓ To find out the current induction inside conducting loop from iron plate.
- ✓ To test the skin depth of the material that is alternative approach to reach this technique.
- ✓ To select the suitable frequency range for transmission signals for metal based on its skin depth.

1.4 The scope of the study

- Electromagnetic techniques are increasingly being demanded for their qualities, this having given rise to a proliferation of many developments in a wide range of applications.
- The research carries wide spectrum of electromagnetic studies.
- An electromagnetic technique plays an important role in Non Destructive Testing (NDT).
- The applications of sensor are limited as it can be only used for Out-line Inspection (OLI) of pipeline.
- Applicable for external corrosion of surface operated pipelines.
- The technique is easy to understand and implement.

1.5 The relevancy of project

A lot of research has been done in electromagnetic field techniques that provides greater performance and ensures the smooth operation of industries. There are several techniques used for the inspection and monitoring of corrosion such as visual inspection, radiography, ultrasonic, eddy current magnetic particle, acoustic emission, leak detection, weight loss coupon etc.

Each technique contains its own application and limitation for installation and commissioning. In such a way, in this project a research study has been conducted to design such a sensor that must be able to detect data of corroded and good metal plate based on electromagnetically induced current.

CHAPTER 2

LITERATURE REVIEW

The literature review will focus on the research study of corrosion, forms of corrosion, its consequences, inspection and measurement techniques. Beside that, the literature research has also been done to find out the information regarding the electromagnetically induced current that helps to inspect the corrosion rate of metal.

2.1 Introduction to corrosion

Corrosion is a degradation of a material that occurs when it reacts with environment. Physicochemical interaction between a metal and its environment which results in changes in properties of the metal and which often lead to impairment of the function of the metal, the environment, or the technical system of which these form a part[3].

The degradation of materials generally occurs via three well-known avenues: corrosion, fracture, and wear. Corrosion is traditionally related to chemical processes that break chemical bonds while fracture is related to mechanical processes that break bonds and wear to relative motion that break bonds. These are, to some extent, separate considerations, but they are also interconnected. Chemical environments accelerate fracture, chemical environments accelerate wear and vice versa as wear products produce deposits that accelerate corrosion, and fracture Processes can permit one component to another contaminate [1].

Corrosion can cause serious failure, which lead to large economic loss, sometimes combined with environmental pollution, or risk of personal injuries. The most important step is in order to reduce the extent of such failures are sufficiently early detection, proper diagnosis and effective prevention measures. [8]

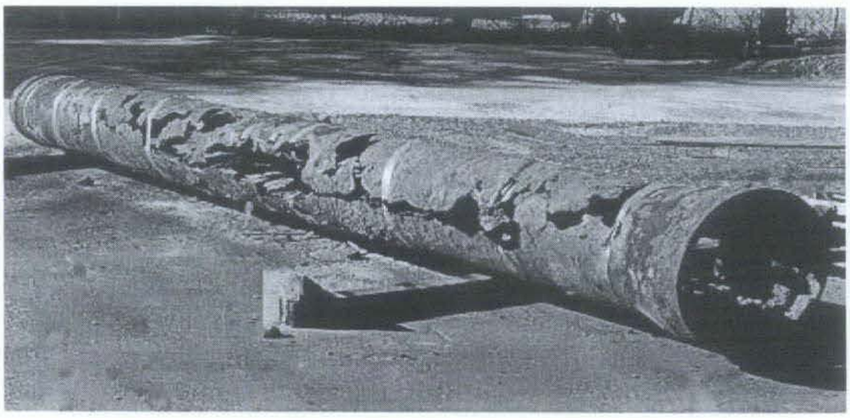

Figure 1: Corroded pipeline

Being in contact with the soil which contains some proportion of humidity, mineral substances and oxygen, a metal construction undergoes an electrochemical reaction, starting to decompose according to the following reaction scheme:

$$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3$$

The equation presents conversion of iron into iron oxide, after being in contact with water and oxygen, resulting in damage of the metal construction as shown in figure (2).

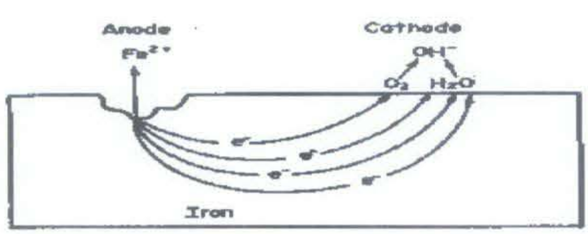

Figure 2: Corrosion reaction of metal

2.2 Forms of corrosion

Corrosion can take many forms, and the statistics associated with each will be different. The actual importance of each corrosion type will also differ between systems, environments, and other operational variables. However, there are surprising similarities in the corrosion failure distributions within the same industries [2].

The few types of corrosion are listed below:

1. Uniform or general corrosion
2. Galvanic or two metal corrosion
3. Thermogalvanic corrosion
4. Crevice corrosion
5. Pitting corrosion
6. Intergranular and exfoliation corrosion
7. Selective corrosion, selective leaching
8. Erosion corrosion
9. Cavitation corrosion
10. Fretting corrosion
11. Stress corrosion cracking
12. Corrosion fatigue

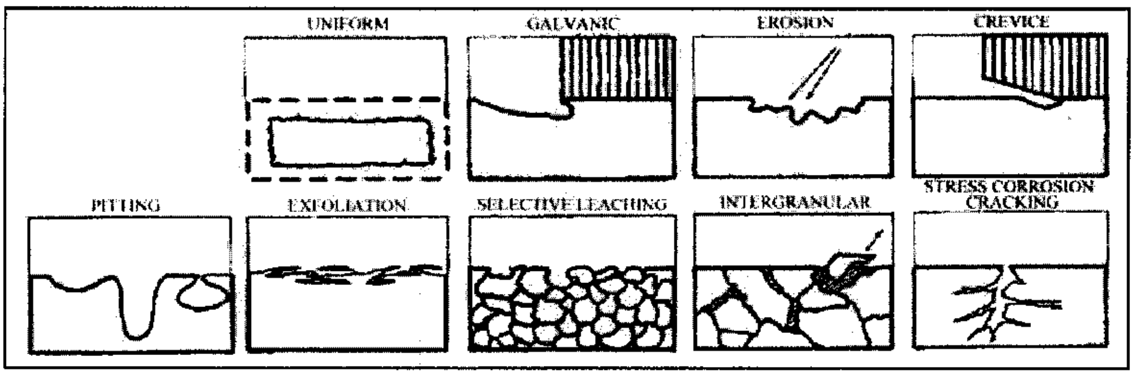

Figure 3: Common forms of corrosion

2.3 Intensity of corrosion:

The intensity of corrosion depends upon many factors; few of those are described as under:

- Type of chemical reaction
- An Environmental affects
- Isolation of tracks
- Isolation of the pipeline network
- Specific ground resistance

2.4 Corrosion Rate measuring units

The corrosion is degradation of material, causes decay in actual thickness of metal. It is measured in meters, inches, and miles or in grams, kilograms etc over certain periods. The several units for corrosion measurement are described below:

- mm/y – millimeters penetration per year
- gmd – grams per square meter per day
- ipy – inches penetration per year
- mpy – mils penetration per year (1000 mil = 1 inch)
- mdd – milligrams per square decimeter per day
- Mils per year (mpy) = 534W/DAT
- mm/y =87.6W/DAT

Where;

W = weight loss in mg,

D = density of specimen material in g/cm^3

A = area in cm^2

T= exposure time in hours

2.5 Consequences of corrosion

Corrosion has many serious economic, health, safety, technological, and cultural consequences to our society [4].

Economic effects:

Studies in a number of countries have attempted to determine the national cost of corrosion. The most extensive of these studies was the one carried out in the United States in 1976 which found that the overall annual cost of metallic corrosion to the U.S. economy was $70 billion, or 4.2% of the gross national product. To get a feeling for the seriousness of this loss, we may compare it to another economic impact everyone is worried about – the importation of foreign crude oil, which cost $45 billion in 1977.

Health effects:

Recent years have seen an increasing use of metal prosthetic devices in the body, such as pins, plates, hip joints, pacemakers, and other implants. New alloys and better techniques of implantation have been developed, but corrosion continues to create problems. Examples include failures through broken connections in pacemakers, inflammation caused by corrosion products in the tissue around implants, and fracture of weight-bearing prosthetic devices. An example of the latter is the use of metallic hip joints, which can alleviate some of the problems of arthritic hips. The situation has improved in recent years, so that hip joints which were was at first limited to persons over 60 are now being used in younger persons, because they will last longer.

Safety effects:

An even more significant problem is corrosion of structures, which can result in severe injuries or even loss of life. Safety is compromised by corrosion contributing to failures of bridges, aircraft, automobiles, gas pipelines etc. – the whole complex of metal structures and devices that make up the modern world.

Technological effects:

The economic consequences of corrosion affect technology. A great deal of the development of new technology is held back by corrosion problems because materials are required to withstand, in many cases simultaneously, higher temperatures, higher pressures, and more highly corrosive environments. Corrosion problems that are less difficult to solve affect solar energy systems, which require alloys to withstand hot circulating heat transfer fluids for long periods of time, and geothermal systems, which require materials to withstand highly concentrated solutions of corrosive salts at high temperatures and pressures. Another example, the drilling for oil in the sea and on land, involves overcoming such corrosion problems as sulfide stress corrosion, microbiological corrosion, and the vast array of difficulties involved in working in the highly corrosive marine environment.

Cultural effects:

International concern was aroused by the disclosure of the serious deterioration of the artistically and culturally significant gilded bronze statues in Venice, Italy. Corrosive processes will accelerate the deterioration of precious artifacts such as those in Venice by the highly polluted environments that now are prevalent in most of the countries of the world. Likewise, inside the world's museums conservators and restorers labor to protect cultural treasures against the ravages of corrosion or to remove its traces from artistically or culturally important artifacts.

2.6 Corrosion Inspection

The corrosion inspection for gas pipeline usually performed in order to know about the rate of corrosion, its causes and effects as shown in figure 4. There are several types of detectors are used for the purpose of corrosion inspection. The inspection usually performed during preventive maintenance (3MPPM or 6MPPM). On the basis of inspection the host companies use to take the decision to maintain the plant smooth operation. Different types of corrosion protection techniques used such as cathodic protection, corrosion inhibitor, and pipeline coding etc [2].

Figure 4: Corrosion rate inspection

2.7 Non-Destructive Testing

The field of Nondestructive Testing (NDT) is a very broad, interdisciplinary field that plays a critical role in assuring that structural components and systems perform their function in a reliable and cost effective fashion. NDT technicians and engineers define and implement tests that locate and characterize material conditions and flaws that might otherwise cause planes to crash, reactors to fail, trains to derail, pipelines to burst, and a variety of less visible, but equally troubling events [7].

These tests are performed in a manner that does not affect the future usefulness of the object or material. In other words, NDT allows parts and materials to be inspected and measured without damaging them. Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost-effectiveness. Generally speaking, NDT applies to industrial inspections. While technologies are used in NDT that are similar to those used in the medical industry, typically nonliving objects are the subjects of the inspections.

2.8 Methods for Non-Destructive Testing

The number of NDT methods that can be used to inspect components and make measurements is large and continues to grow. Researchers continue to find new ways of applying physics and other scientific disciplines to develop better NDT methods. However, there are few NDT methods that are used most often. These methods are visual inspection, penetrant testing, magnetic particle testing, electromagnetic or eddy current testing, radiography, and ultrasonic testing. These methods are briefly described below [7].

1. Visual and Optical Testing (VT)

Visual inspection involves using an inspector's eyes to look for defects. The inspector may also use special tools such as magnifying glasses, mirrors, or bore scopes to gain access and more closely inspect the subject area. Visual examiners follow procedures that range from simple to very complex.

2. Penetrant Testing (PT)

Test objects are coated with visible or fluorescent dye solution. Excess dye is then removed from the surface, and a developer is applied. The developer acts as blotter, drawing trapped penetrant out of imperfections open to the surface.

With visible dyes, vivid color contrasts between the penetrant and developer make "bleedout" easy to see. With fluorescent dyes, ultraviolet light is used to make the bleedout fluoresce brightly, thus allowing imperfections to be readily seen.

3. Magnetic Particle Testing (MT)

This NDE method is accomplished by inducing a magnetic field in a ferromagnetic material and then dusting the surface with iron particles (either dry or suspended in liquid). Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections, previewing a visual indication of the flaw.

4. Electromagnetic Testing (ET) or Eddy Current Testing

Electrical currents are generated in a conductive material by an induced alternating magnetic field. The electrical currents are called eddy currents because they flow in circles at and just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the materials conductive and permeability properties, can be detected with the proper equipment.

5. Radiography (RT)

Radiography involves the use of penetrating gamma or X-radiation to examine parts and products for imperfections. An X-ray generator or radioactive isotope is used as a source of radiation. Radiation is directed through a part and onto film or other imaging media. The resulting shadowgraph shows the dimensional features of the part. Possible imperfections are indicated as density changes on the film in the same manner as medical X-ray shows broken bones.

6. Ultrasonic Testing (UT)

Ultrasonic's use transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces.

7. Acoustic Emission Testing (AE)

When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." As in ultrasonic testing, acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity, rate, and location.

8. Leak Testing (LT)

Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas penetrant techniques, and/or a simple soap-bubble test.

2.9 Electromagnetic Concepts/theories

2.9.1 Electromagnetic Induction

An electric current can experience a force when placed in a magnetic field and an electric current produces a magnetic field. In 1831, Faraday and Henry discovered that a changing magnetic field can produce an electric current while constant/uniform magnetic field does not produce a current, as shown in figure 5.

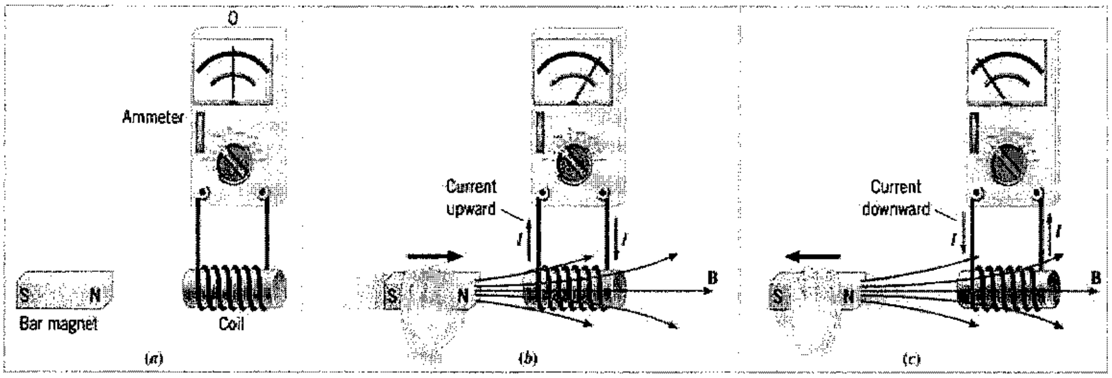

Figure 5: Current induction due to change in magnetic field [7]

A current can also appear in a coil of wire in a constant magnetic field, if the area of the coil is changing. The current created by changing the field or the coil area is called an induced current. When the induced current appears, the coil behaves as if it had a voltage source called an induced emf.

Process of generating a current by using a magnetic field is sometimes called motional emf or is also be known as electromagnetic induction.

$$\xi = BLv\sin\theta$$

Where emf is the potential difference measured in volts, v is the velocity with which the wire is moved through the magnetic field B, θ is the angle at which the wire is moved in the magnetic field, and L is the length of the wire.

Faraday found that the amount of emf induced in a coil of wire depended upon how rapidly the magnetic field changes in the coil of wire. The faster the magnetic field changes, the greater the induced emf. If the flux through a coil contain N loops of wire changes by an amount $\Delta\Phi$ during a time Δt. Where negative sign indicates the direction in which the induced emf acts.

$$\xi = -N \frac{\Delta\Phi}{\Delta t}$$

The process where current is produced when either a wire or a magnetic field move relative to one another, as long as the wire cuts across magnetic field lines during the motion, a current is produced, a current is induced in a coil of wire if it is moved into or out of a magnetic field, a current is induced in a coil of wire if a magnet is inserted or removed from the coil of wire. It doesn't matter if the magnet or the coil moves-motion or change is required to induce an emf.

Induced current is related to the motion of the conductor in the magnetic field. The direction of the induced current is directly related to the direction of motion of the conductor in the magnetic field. Direction is dependent on the motion of the B-field or the conductor. The motion of the conductor is perpendicular to the B-field.

2.9.2 Direction of induced current

- Determine whether the magnetic field strength is increasing or decreasing.
- Determine the direction in which the original field enters the coil.
- Determine the direction of the induced magnetic field so that it opposes the change in the magnetic flux.
- Use RHR to predict the direction of the current knowing the direction of the induced magnetic field.

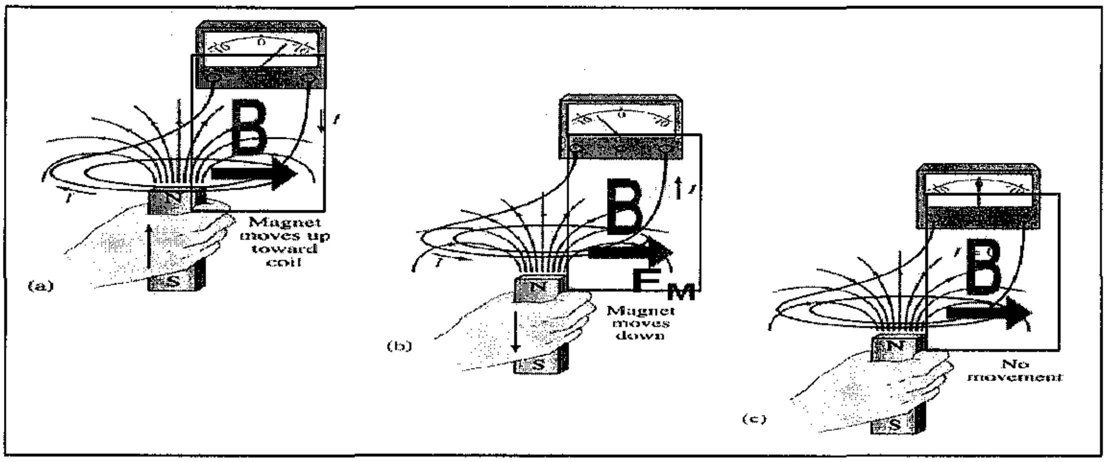

Figure 6: Direction of current and magnetic field [7]

Electrons only flow when the conductor is moving through the magnetic field. Charges flow only when the bar magnet is moving into or out of the coil or when the coil moves relative to the magnet.

Field produced by a long straight conductor, if a circular path of radius r is considered around the conductor carrying a current I, then the field H along this path would be constant by symmetry.

$$H = \frac{I}{2\pi r}$$

2.9.3 Moving conductor in a static Magnetic Field

Consider a wire of length l moving across a static magnetic field **B** at constant velocity **u**, as shown in figure 7. The conducting wire contains free electrons, the magnetic force $\mathbf{F}_m$ acting on any charged particle q moving with a velocity **u** in a magnetic field **B** is given by;

$$\mathbf{Fm} = q\,(\mathbf{u} \times \mathbf{B})$$

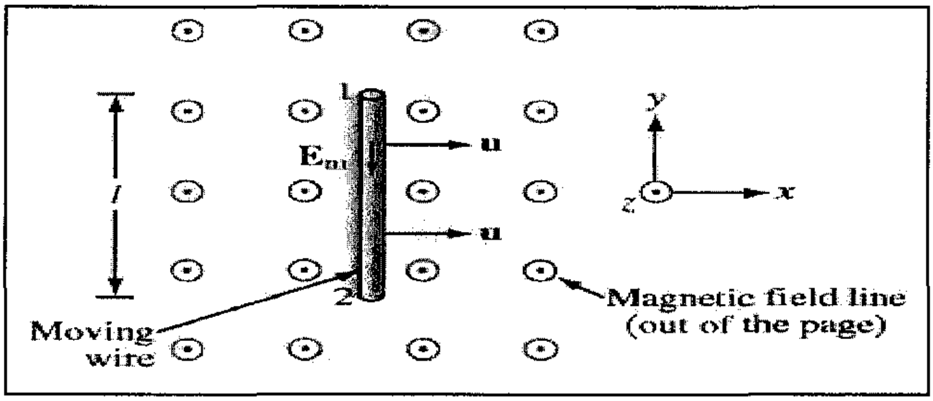

Figure 7: Conducting wire in a static magnetic field [9]

This magnetic force is equivalent to the electrical force that would be exerted on the particle by an electric field $\mathbf{E}_m$ given by

$$\mathrm{Em} = \frac{Fm}{q} = u \times B$$

The field $\mathbf{E}_m$ generated by the motion of the charged particle is called a motional electric field, and it is in a direction perpendicular to the plane containing **u** and **B**. For the wire shown in Fig 7, $\mathbf{E}_m$ is along $-\hat{y}$. The magnetic force acting on the electrons in the wire causes them to move in the direction of $-\mathbf{E}_m$; that is, toward the end labeled 1 in figure 7. This in turn induces a voltage difference between ends 1 and 2, with end 2 being at higher potential. The induced voltage is called a motional emf, and is define as the line integral of $\mathbf{E}_m$ between ends 2 and 1 of the wire,

$$V_{emf} = V_{12} = \int_2^1 E_m . dl = \int_2^1 (u \times B).dl$$

For the conducting wire, $u \times B = \hat{x}u \times \hat{z}B_o = -\hat{y}uB_o$ and $dl = \hat{y}dl$ hence,

$$V_{emf} = V_{12} = -uB_o l$$

In general, if any segment of a closed circuit a with contour C moves with velocity **u** across a static magnetic field **B**, then the induced motional emf is given by

$$V_{emf} = \oint_C (u \times B).dl$$

2.10 EMI corrosion detecting technique

In this project, the induced current due to electromagnetic field is used to detect corrosion rate. Current flows in the metal plate due to the voltage supplied and metal plate contains magnetic field around it. When conducting loop is placed and moved near the magnetic flux, electromagnetically induced current will flow in the conducting loop. The magnitude of electromagnetically induced current should be proportionate to the thickness of the metal structure, and the electromagnetically induced current should be lower if the loop is near a corroded region of the metal.

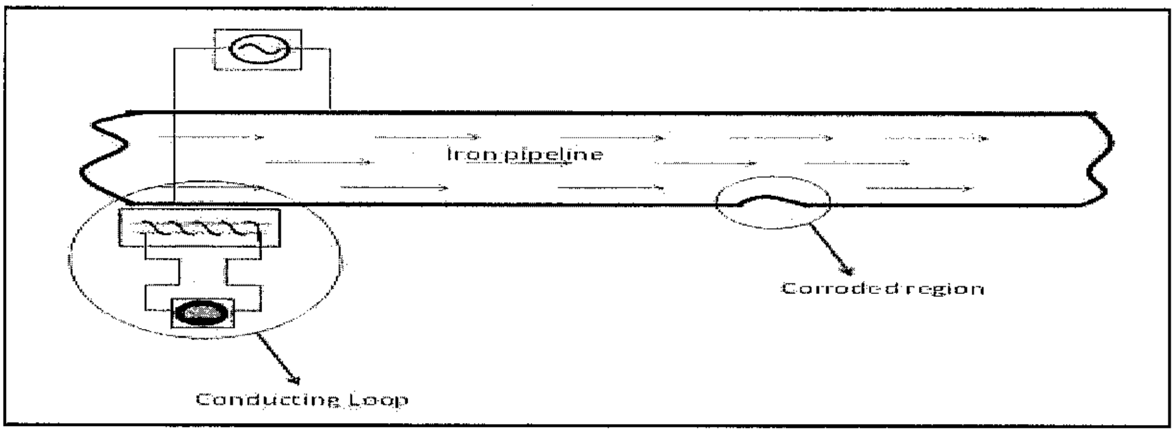

Figure 8: Conducting loop away from corroded region of pipeline

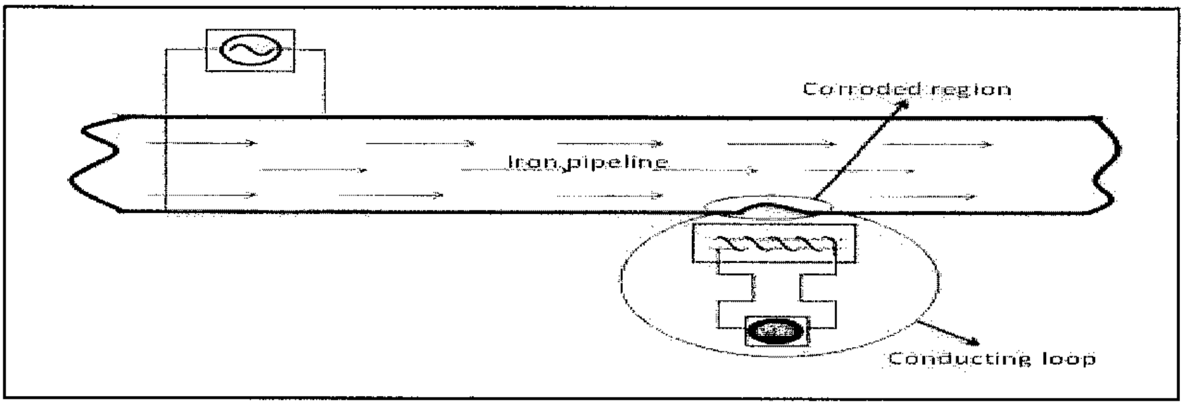

Figure 9: Conducting loop near to a corroded region of pipeline

As about the technique discussed before, here figure (8a) and figure (8b) are based on the same technique. The figure 8a shows the effect on induced current in the conducting loop when it is placed away from the corroded region of the metal. When the conducting loop placed near the corroded region of metal structure, an ammeter connecting to conducting loop will display few amount of current induced in conducting loop, and when it will be moved with some certain velocity, it will continuously display amperes. Once it reached or placed near a corroded region of metal figure (8b), the variation in current amperes will be displayed on ammeter. As mentioned before that the magnitude of electromagnetically induced current is proportionate to the thickness of the metal, the electromagnetically induced current will be lower if the loop is near the corroded region of the metal.

2.11 Corrosion rate measurement

2.11.1 Corrosion rate

Corrosion rate is the amount of corrosion that occurs during a specified period of time. In most cases, we express it as millimeter of metal loss per year, as expressed in section 2.3. The formula shown below can be used to calculate the rate of corrosion.

Where

$$C = \frac{TO - TA}{Time}$$

C= The corrosion rate, represented in the millimeters per year

TO= Thickness original, measured in millimeters

TA=Thickness actual, measured in millimeters

Time=Operating period, measured in year

Remember that C is not constant. There are fluctuations in the chemical components of the various products that cause corrosion. These fluctuations can cause corrosion to increase or increase during a given run. A variation of the general corrosion rate formula can be used to calculate C for a specific run.

$$C_1 = \frac{TA_1 - TA}{Time}$$

Where

C_1 = the previous run's corrosion rate, represented in millimeters per year

TA_1= TA from the previous inspection, measured in millimeters

TA= the current TA, measured in millimeters

Time= the length of the previous run, measured in years

We can then compare C to C1 in order to determine whether the corrosion rate has increased during the previous run. If it has, operations must be notified so that they can determine what is causing the increase and take the necessary steps [11].

2.11.2 Remaining Corrosion Allowance

The remaining corrosion Allowance (RCA) is the amount of metal left in the pipe wall beyond the TM after the piping has been in service for some period of time. Piping is kept in service as long as there is sufficient RCA. RCA is calculated with a sample formula [11].

$$RCA = TA - TM$$

2.11.3 Calculating RL and the Inspection Interval

To calculate remaining life (RL), we divide the remaining corrosion rate; the piping is inspected again when half the RL has passed by. For example, if RL is 3 years, the piping must be inspected again in 1.5 years:

$$NI = \frac{RL}{2}$$

Where; NI=Next inspection interval, expressed in years.

NI let us determine whether the piping will limit the next run. For example ,if RL for a given section of piping is 4 years and the run is 3 years, NI-one half of RL-limits the run [11].

2.12 Advantages of electromagnetic techniques

Techniques based on the electromagnetic effect have certain advantages over others, such as ultrasonic or magnetic particle techniques, making them more suitable for many applications. Among these characteristics is the fact that no coupling medium is required and that they do not even need to be in contact with the surface scanned, along with the possibility of using high scan speeds.

The techniques allow defects to be located and dimensioned with high levels of repeatability, and make it possible to produce records that are long-lasting and open to analysis over time.

2.13 Permittivity of metal

2.13.1 Introduction

Permittivity is a physical quantity that describes how an electric field affects, and is affected by a dielectric medium, and is determined by the ability of a material to polarize in response to the field, and thereby reduce the total electric field inside the material. Thus, permittivity relates to a material's ability to transmit or permit an electric field [9].

In SI units, permittivity is measured in farads per meter (F/m).The constant value ε0 is known as the electric constant or the permittivity of free space, and has the value ε0 $\approx 8.845 \times 10^{-12}$ F/m.

2.13.2 Mathematical description

$$D = \varepsilon E$$

$$\varepsilon = \varepsilon_r \varepsilon_o$$

Where ε=Electrical permittivity

D=Field density

E =Electrical field

ε_0 =Permittivity of free space (8.845×10^{-12} F/m)

ε_r = Relative permittivity

2.13.3 Permittivity testing

In order to measure the permittivity of metal, there are several ways to use. There are direct and indirect methods, it depends upon the metal and its structure. Here in this project the permittivity of iron plate is measured indirectly by using impedance analyzer (Agilent 2494A).

The calculation of permittivity contains following steps [6]:

1. Measure the parallel capacitance Cp of plate.
2. Put the Cp value in formula given below:

$$\varepsilon_r = \frac{t_m \times C_p}{A \times \varepsilon_0} = \frac{t_m \times C_p}{\pi \left(\frac{d}{2}\right) 2 \times \varepsilon_0}$$

Where

tm= Average thickness of test material[m]

Cp= Equivalent parallel capacitance

A= Area of guarded electrodes [m^2]

d= Diameter of guarded electrode [m]

ε_0 =Permittivity of free space (8.845×10^{-12} F/m)

ε_r = Relative permittivity

3. The permittivity of material can be calculated by following formula:

$\varepsilon = \varepsilon_r \varepsilon_0$

Where

ε_0 =Permittivity of free space (8.845×10^{-12} F/m)

ε_r = Relative permittivity

The permittivity of metal was tested on several frequencies (40Hz-110MHz).

2.14 Skin depth of metal

2.14.1 Introduction

RF wave's techniques can be utilized as an Alternative to current induction technique. In this case the RF waves can be impinged into metal structure. The skin depth of the impinging the RF waves is important to reach the technique.

It is measure of distance an alternating current can penetrate beneath the surface of conductor. Skin depth is the property of material that varies with the frequency applied wave. It can be calculated from the relative permittivity and conductivity of material and frequency [5].

Skin depth also varies as the inverse square root of the permeability of the conductor. In the case of iron, its conductivity is about 1/7 that of copper. Its permeability is about 10,000 times greater however. The skin depth for iron is about 1/38 that of copper or about 220 microns at 60 Hz [5].

2.14.2 Mathematical description

$$\delta s = \sqrt{\frac{2}{2\pi f \times \mu\sigma}}$$

$$\mu = \mu_r \mu_o$$

$$\sigma = \frac{1}{\rho}$$

Where

∂s= Skin depth μ_o =Permeability of free space ($4\ \pi * 10^{-7}$ H/m)

μ=Permeability of material σ =Conductivity of material (mho/m)

μ_r = Relative permeability of material, ρ= Resistivity of material (Ω/m)

2.14.3 Skin depth calculation

In order to calculate the skin depth of the metal, formulas given in section no: 2.13.2 were used and it was noticed that increase in frequency cause decay in the skin depth of the material. The results for skin depth test are given in chapter 4.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

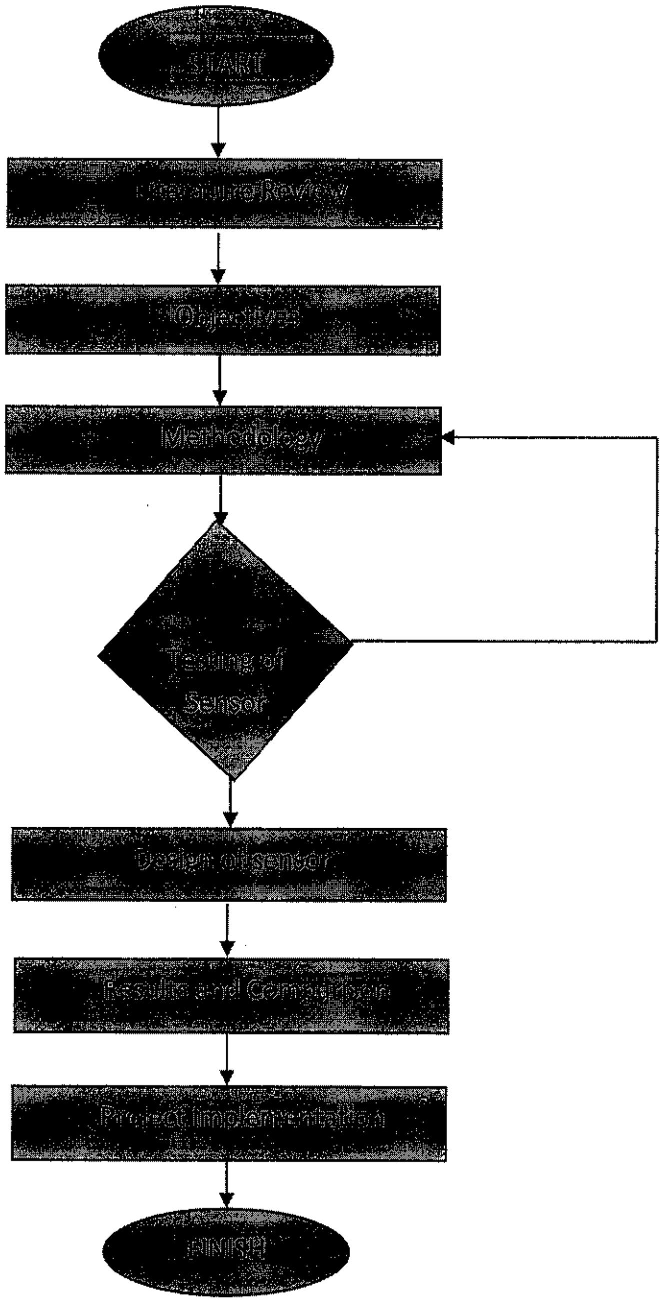

Figure 10: Flow chart of the Final Year Project

The planning of project has been done to make sure the project work goes smoothly. Beside that, the time limitations are taken into consideration. The right procedures have been identified in order to complete the project work. Figure 9 shows the project flows for author planning.

The project has gone through a few phases of procedure. The main activity conducted during first 8 weeks was literature review concerning about the study about the basic knowledge of corrosion and electromagnetic techniques that are used to detect the corrosion of any metal structure.

Literature review was done to gain the necessary knowledge of the theory involved before design of conducting loop and all others related tests. The literature review was done by studying various texts from university resources center and also form internet. Beside that, the manual for Impedance analyzer was also included in studies.

To proceed with design phase of the project, data from various sources were required. This information was collected from several references book, catalogues and manuals etc. The conducting loop was then designed based on the guidelines obtained. From the basic design, it was refined and improved from time to time until the final design was completed.

After designing the conducting loop, and testing of electromagnetic induction inside the loop, the test for skin depth was conducted.

The skin depth of metal was found by measuring the parallel capacitance and permittivity of metal by using the impedance analyzer. This testing helped author to find the skin depth of metal and suitable frequency for transmitted signals. The test was conducted from 40 Hz to 110 MHz

3.2 Tools and Equipments required

- A sample of metal plate
- A conducting loop
- AC power supply
- Multimeter
- Impedance Analyzer

3.3 Conducting loop

In order to detect current, a conducting loop is used. The conducting loop consists of aluminum as its medium and copper wire that was wrapped around it. The specification of conducting loop is detailed in table 1 and designed loop is given in figure 10.

Table 1: Specifications of conducting loop

DATA	VALUE/NAME
Medium	Aluminum
Wiring	Copper
Length of conducting loop	7cm
Number of turn of conducting loop	50
Diameter of conducting loop	3.1cm

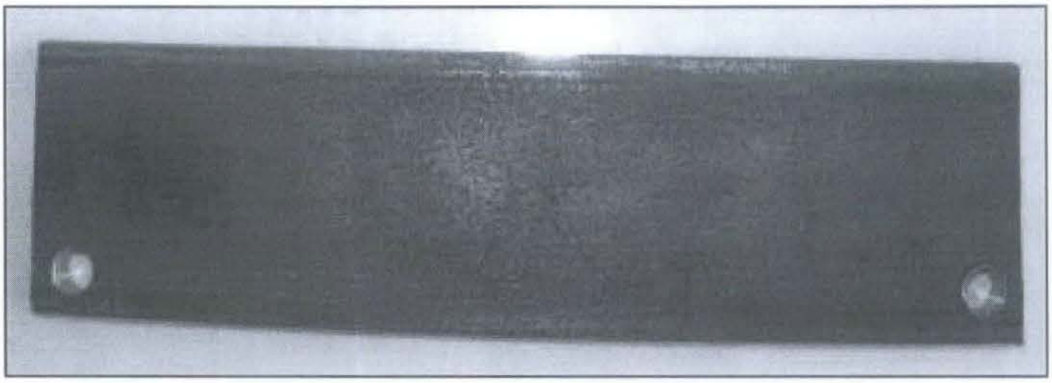

Figure 12: A sample of metal plate

3.5 Electromagnetic induction in conducting loop

When conducting loop placed and moved near the metal plate causes the electromagnetic induction in conducting loop because of change in magnetic field around it, as explained in section 2.9.

The resistance in the plate is 0.03401Ω and resistance of coil is 2.6154 μΩ

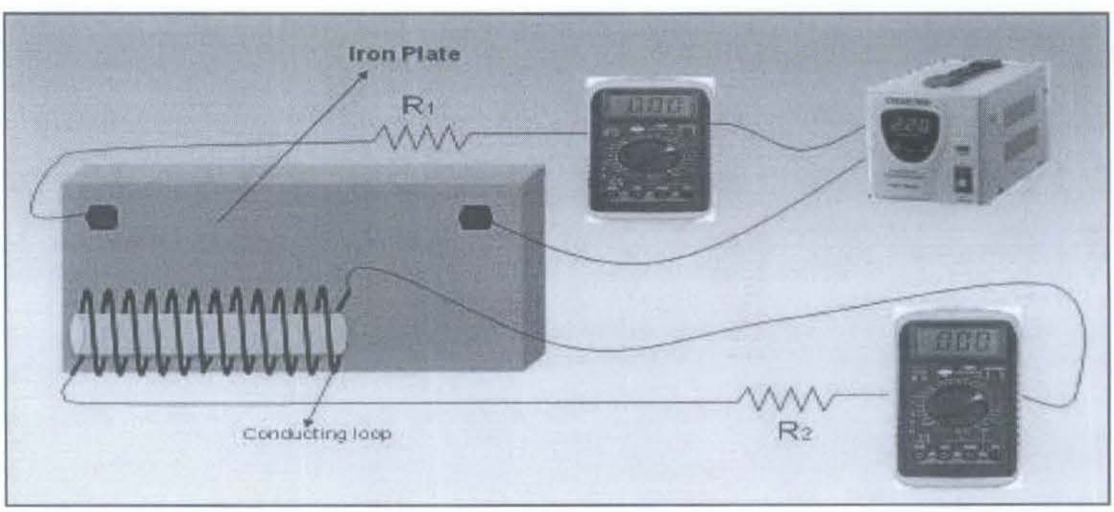

Figure 13: Electromagnetic induction circuit

Based on conducting loop and metal plate, calculation has been done in order to know about the magnetic field in the metal plate and the current inductions in conducting loop (Appendix II),

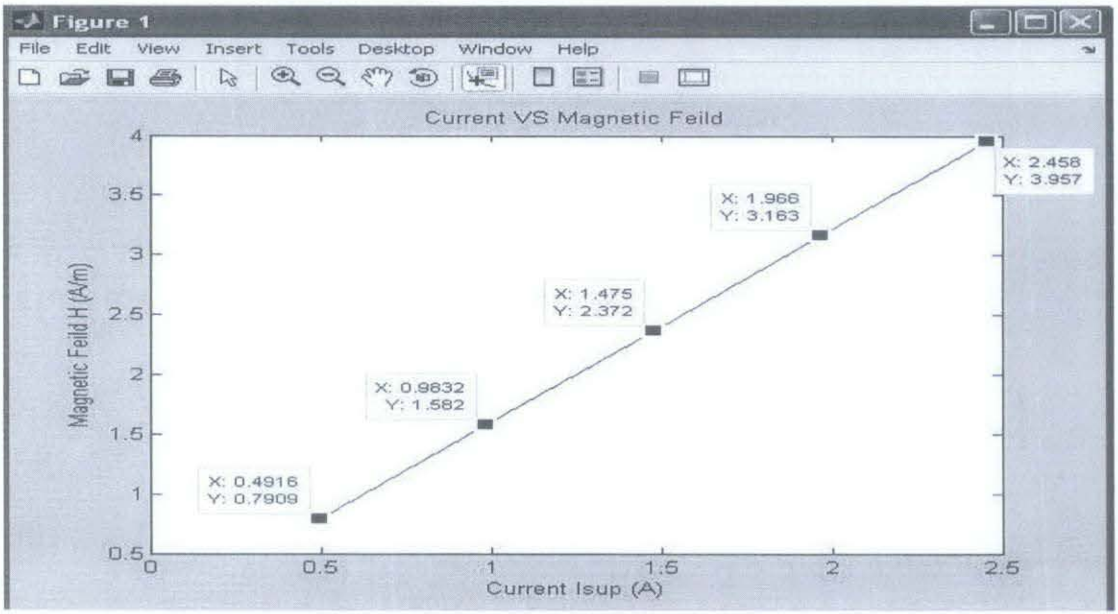

Figure 14: Magnetic field in metal plate due to current flow

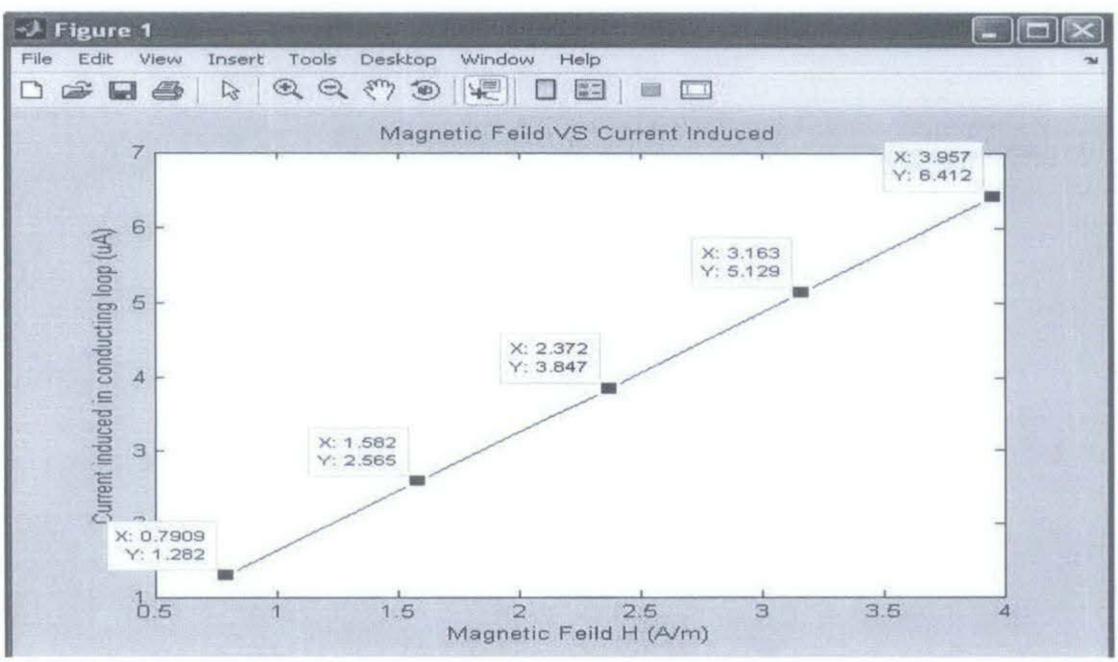

Figure 15: Current induced in conducting loop

3.6 Skin depth testing of metal structure

To calculate the skin depth of metal structure a test was conducted by using impedance analyzer (Agilent 2494A) as shown in figure 16. Calculation was done by applying the steps given in section 2.12 and 2.13.It contains few objectives to achieve as described below:

- Distance of penetration beneath the surface of conductor.
- Effect of frequency variation on metal permittivity and skin depth.
- Selection of suitable frequency range for transmission waves.

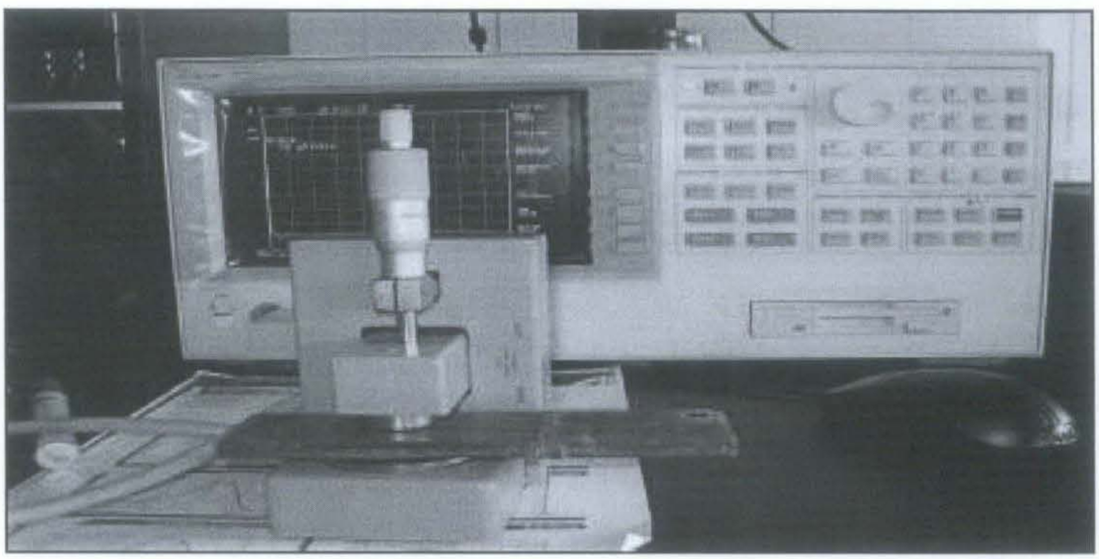

Figure 16: Parallel capacitance of metal by using Impedance analyzer

3.7 Flow chart for Cp measurement

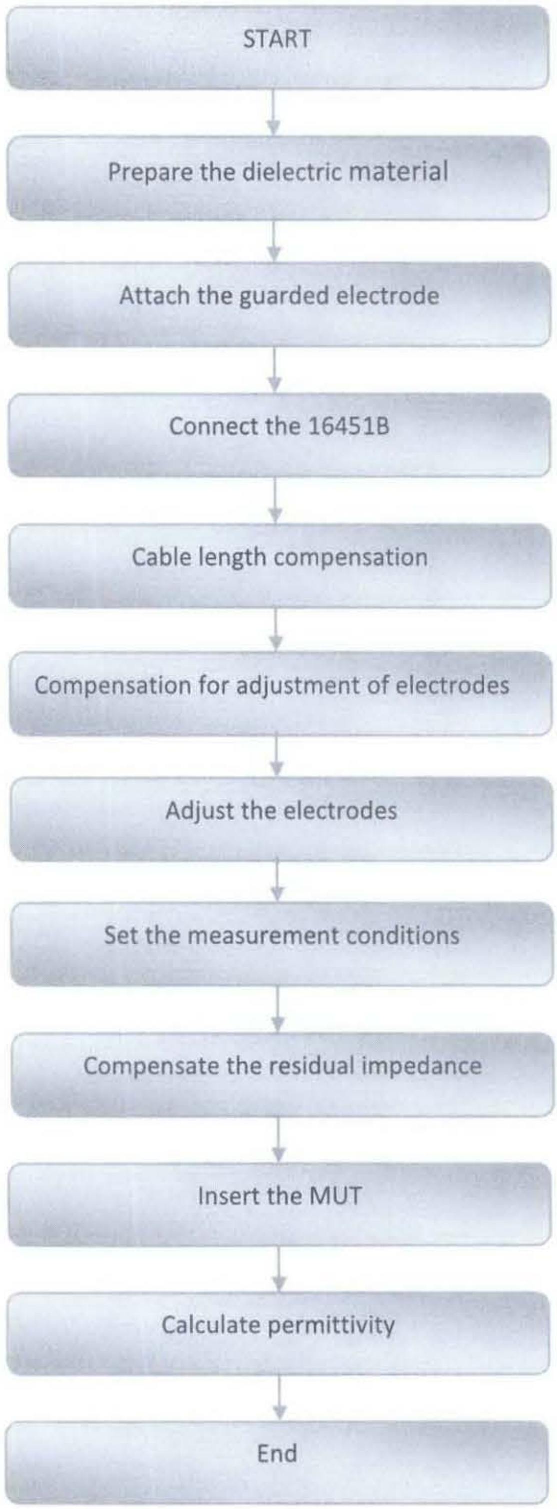

Figure 17: Measurement flow chart [6]

Figure 17 shows measurement procedure flow chart for parallel capacitance. As mentioned in earlier chapters that permittivity can be measured by indirect method. Here figure 3.1 shows steps for the measurement of parallel capacitance and calculation of relative permittivity. With the help of Cp value, permittivity of metal can be calculated easily (section 2.12.3).

The method to find out skin depth value is not by measurement, it is by calculation. Detailed procedure to calculate skin depth of metal is given in section 2.13 and its results are given in chapter no: 4.

3.8 Testing of corroded metal

The same test was being performed as described in section 3.4 for the corroded metal. The figure 18 shows the difference between corroded and non corroded metal plate and their results are given in chapter no 4.

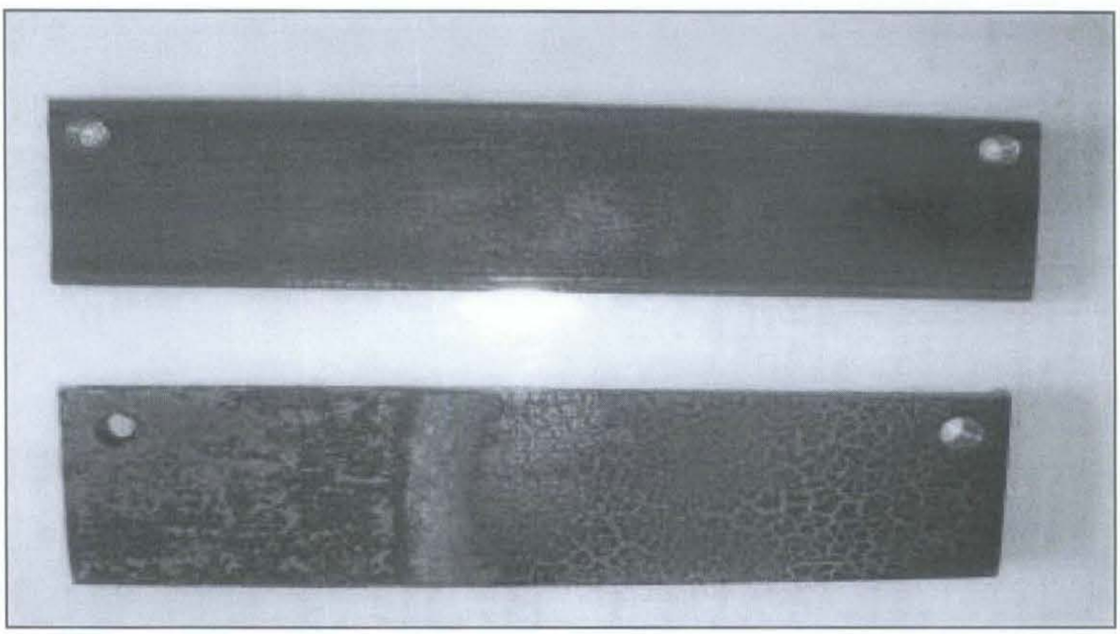

Figure 18: Sample of corroded and non-corroded metal

CHAPTER 4

RESULTS AND DISCUSSION

This chapter summarizes the results and discussion part of the project. It shows the calculated results of electromagnetic induction inside the conducting loop and results for the skin depth test of the metal plate.

4.1 Test of Conducting Loop

The conducting loop has been used for the current induction from the metal plate, where current is allowed to flow through the metal plate as detailed in section 2.9. The metal plate contains magnetic field around it and if a conducting loop is placed and moved near the magnetic flux, electromagnetically induced current will flow in the conducting loop. The magnitude of electromagnetically induced current should be proportional to the thickness of the metal plate, and electromagnetically induced current in conducting loop changes when the thickness of the metal plate changes.

Placing and moving the conducting loop near a metal plate results the electromagnetic induction in the conducting loop. The amount of current depends upon the strength of magnetic field around the metal.

4.2 Calculated Magnetic field in metal plate

In order to know about magnetic field that takes place around metal due to current flows, a few calculations has been done based on the electromagnetic theories (Appendix II). Where from one can be able to observe the effects of current varying in the metal structure. The change in current flows in the metal structure also changes the magnetic field of metal plate. The current density changes with the change in the area of plate. The graphical representation of electromagnetic field around metal is given in figure 19.

Table (3): Magnetic field around metal plate

Voltage (V)	Resistance (Ω)	I_{plate} (A)	H (A/m)
1	2.03401	0.4916	0.7909
2	2.03401	0.9832	1.5818
3	2.03401	1.4749	2.372
4	2.03401	1.9665	3.1633
5	2.03401	2.4581	3.9546

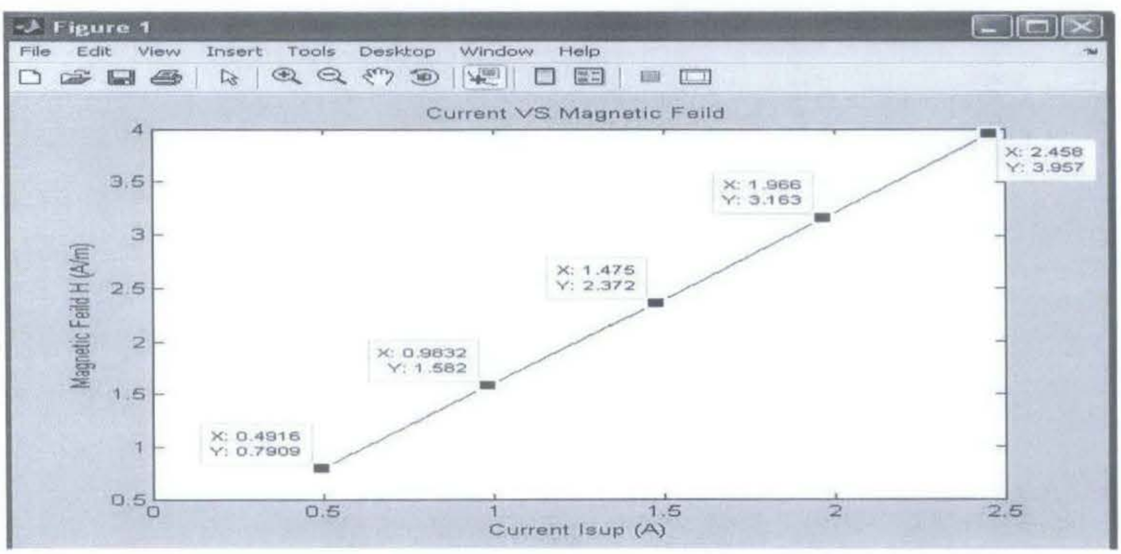

Figure 19: Magnetic field around metal plate

The variation in thickness of metal causes the change in volume current density that also affects on magnetic field of the metal. Due to which the electromagnetically induced current in the conducting loop will also be affected. Fig (19) shows the linear relationship of current flow in metal and magnetic field around it.

4.3 Calculated Current induction in conducting loop

Figure (20) shows the current induced in conducting loop. Current induction takes place when a conducting loop is placed and moved near a metal plate. When it is moved, there will be a change in magnetic field around it causes the current induction in the conducting loop.

Table (4): Current induced in conducting loop

V_{ind} (μV)	R_{coil} ($\mu\Omega$)	I_{ind} (μA)
3.3539	2.6154	1.282
6.7078	2.6154	2.5647
10.062	2.6154	3.8472
13.416	2.6154	5.129
16.770	2.6154	6.142

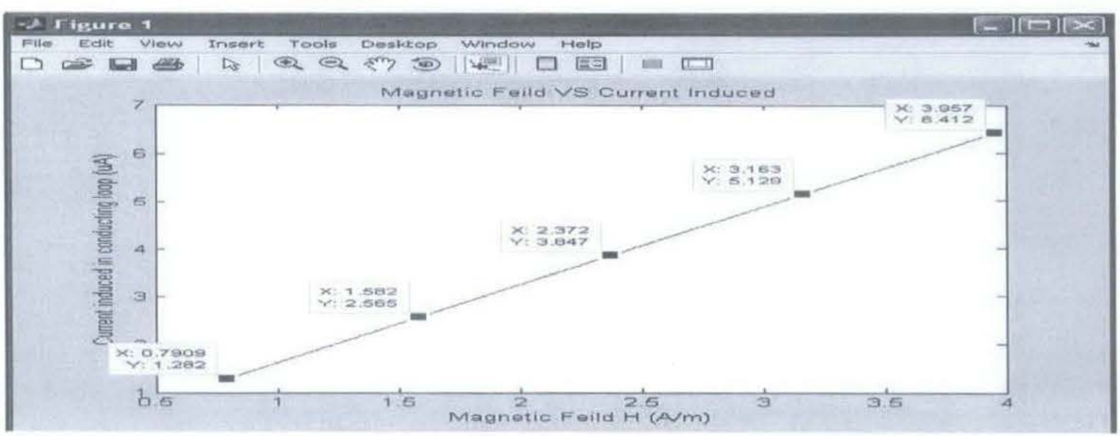

Figure 20: Current induced in conducting loop

Electromagnetic induction depends upon the strength of magnetic field around the metal plate and magnetic field varies with the change of current flows through the metal plate. As the magnetic field around the metal is increasing, the current inductions in conducting loop also increasing.

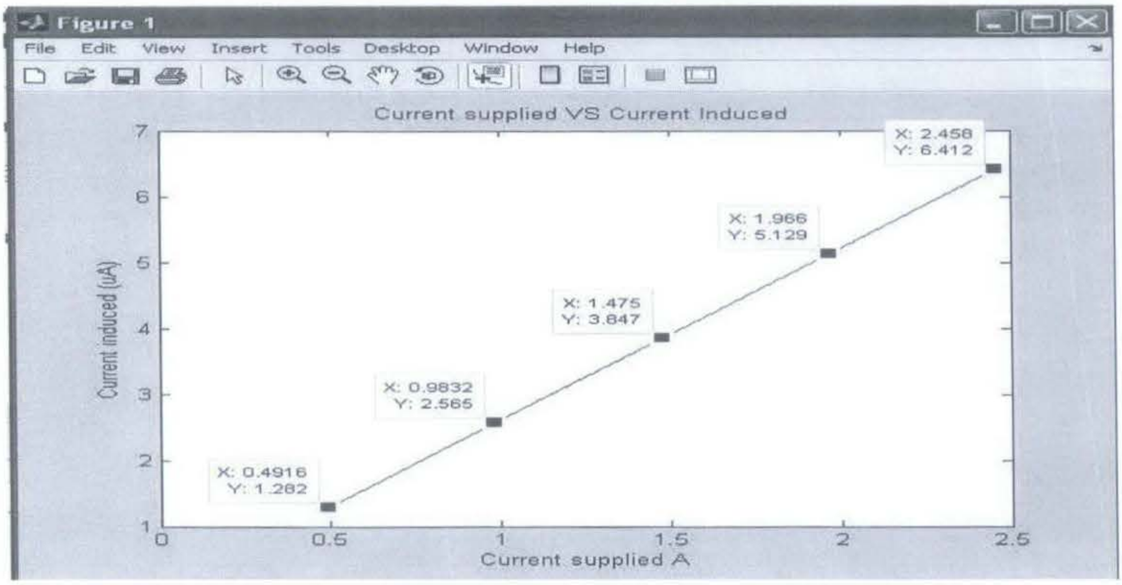

Figure (21): Current flow in metal plate and current induced in conducting loop

Figure (21) shows the graph for current flows in the metal plate and current induced in the conducting loop. Thus it can be noticed from the graph the current induced in the conducting loop is lower than the current flows in the metal plate. The conducting current is in proportional with current supplied, and winding losses and resistance also effect the current induced that why the values of current induced in conducting loop in micro amperes.

4.4 Permittivity of metal

Fig (21) shows the sample of a metal that has been used to generate the magnetic field around it. As discussed before about an alternative approach for this technique that is Skin depth of the metal. In order calculate the skin depth of metal; it is must to know about the permittivity of the metal.

Figure 22: Sample of metal

The test for permittivity was done by using the impedance analyzer and its frequency range is from 40 Hz to 110 MHz. Fig (22) shows that the permittivity of metal increases with the increase of frequency.

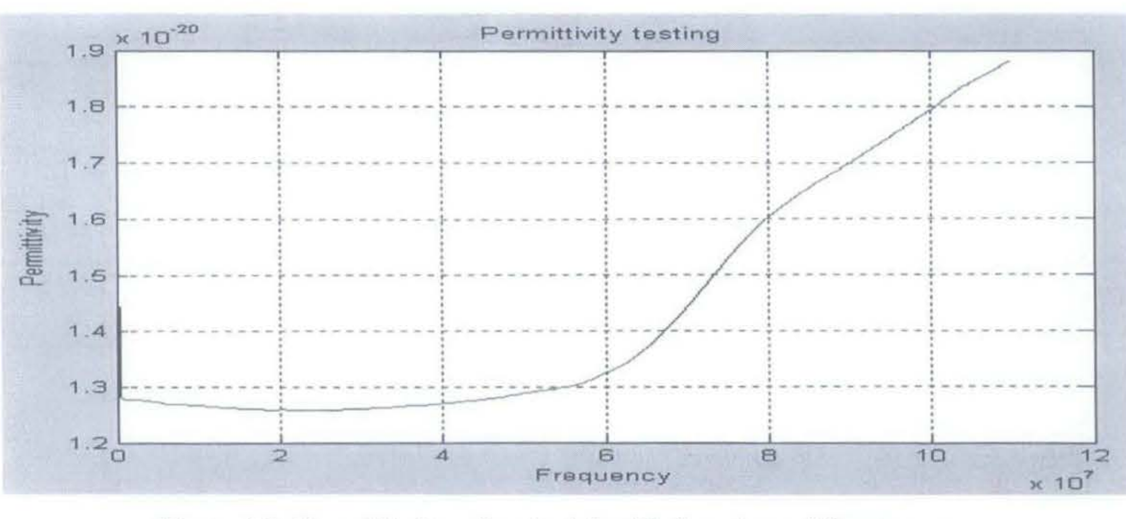

Figure 23: Permittivity of material with function of frequency

4.5 Skin depth of metal

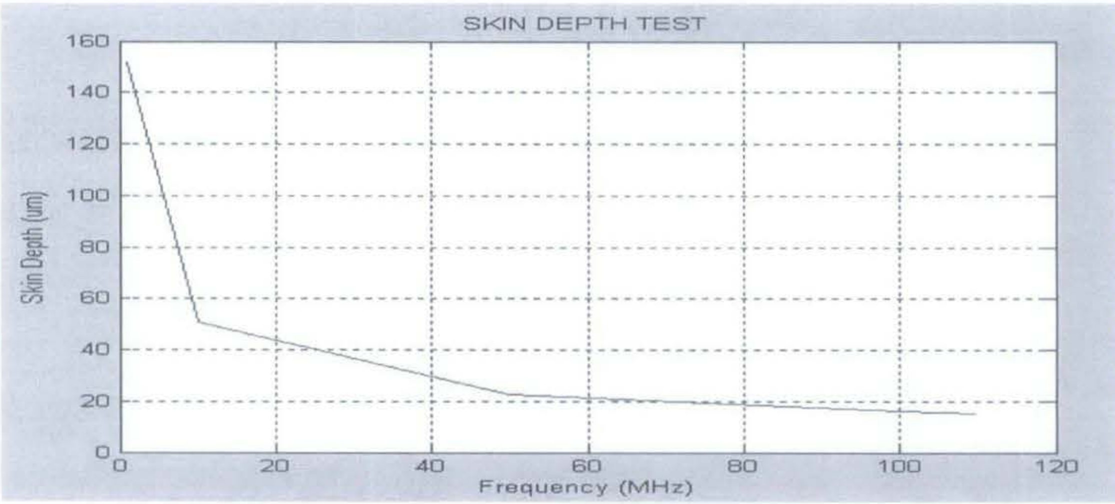

Figure 24: Skin depth of material with the function of frequency

The figure 23 shows the graph of skin depth versus frequency where the skin depth of metal decreases when the frequency increases. The test was conducted from 40 Hz to 110 Hz. Skin depth varies as the inverse square root of the conductivity. This means that better conductors have a reduced skin depth. The overall resistance of the better conductor is lower even though the skin depth is less.

Skin depth also varies as the inverse square root of the permeability of the conductor. In the case of iron, its conductivity is about 1/7 that of copper. Its permeability is about 10,000 times greater however. The skin depth for iron is about 1/38 that of copper or about 220 microns at 60 Hz. Thus the skin depth of the meal decreases with the increase in frequency. Low frequency can provide the better results in the in the comparison of high frequency.

4.5 Skin depth of metal

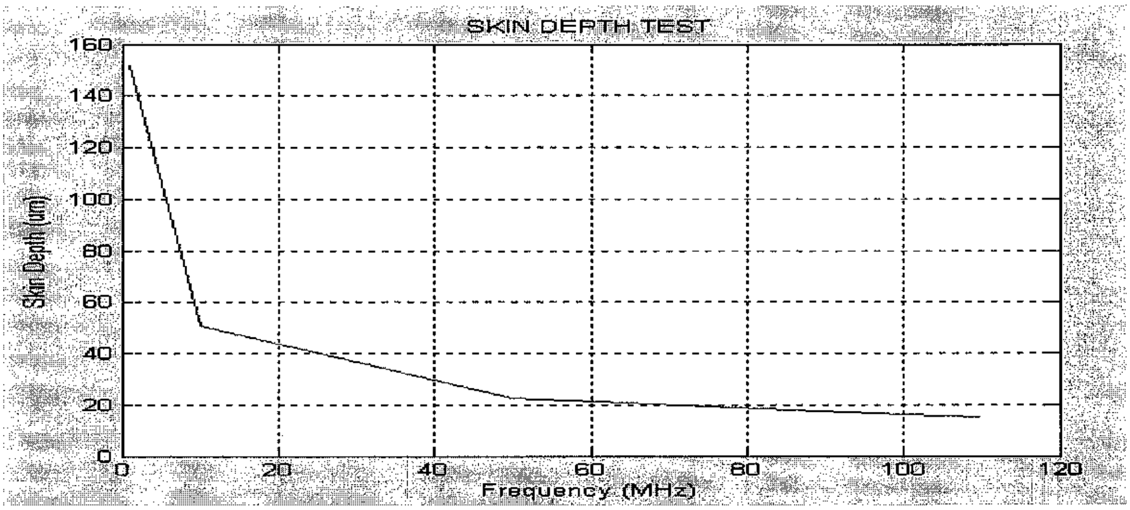

Figure 24: Skin depth of material with the function of frequency

The figure 23 shows the graph of skin depth versus frequency where the skin depth of metal decreases when the frequency increases. The test was conducted from 40 Hz to 110 Hz. Skin depth varies as the inverse square root of the conductivity. This means that better conductors have a reduced skin depth. The overall resistance of the better conductor is lower even though the skin depth is less.

Skin depth also varies as the inverse square root of the permeability of the conductor. In the case of iron, its conductivity is about 1/7 that of copper. Its permeability is about 10,000 times greater however. The skin depth for iron is about 1/38 that of copper or about 220 microns at 60 Hz. Thus the skin depth of the meal decreases with the increase in frequency. Low frequency can provide the better results in the in the comparison of high frequency.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This chapter includes the conclusion and recommendation part of project report. The over all precised summary of project along with recommendations are shown in this chapter.

5.1 Conclusion

Electromagnetic induction is a suitable technique for measuring current of any conductor. Electromagnetic concepts contain a wide spectrum in various fields, and most of sensors are designed with the use of magnetic field. The technique is easily to apply, design and implement and it contains various applications in practical life.

This project is based on electromagnetic induction. The magnetic field is used to induce the current in the conducting loop. The amounts of current identify the thickness of metal. The magnitude of current induced in the conducting loop from a metal is directly proportional to the thickness of metal.

Corrosion is the degradation of metal, it reduced the thickness of metal due to which current density decreases and magnetic field around it will also be decreased. When a conducting loop is placed and moved near metal, a certain amount of current induced in the conducting loop due to the change in magnetic field around metal plate.

RF wave's techniques can also be utilized as an Alternative to current induction technique. In this case the RF waves can be impinged into metal plate. The skin depth of the impinging the RF waves is important to reach the technique.

5.2 Recommendations

In order to increase the amount of current induced in conducting loop, it is recommended to do the proper winding of conducting loop, increase the size of conducting loop and number of turns.

Improving the magnetic field around the metal plate can enhance the performance of conducting loop. A good conductor allows more current to flow, in its result the more magnetic field will take place around it.

By improving the conducting loop performance it will be easier to induce current. Based on the amount of current induced in the conducting loop it will be more helpful to differentiate in between the various thicknesses of metal. Because as mentioned in previous chapters that amount of current induced in conducting loop is proportional to the thickness of metal.

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APPENDICES

Acronyms

Alternating Current (AC): Electric current that reverses direction periodically (usually many times per second).

Ammeter: An instrument for measuring the magnitude of electric current in a circuit.

Ampere: A standard unit of measure for electric current or the flow of electrons. The amount of current sent by one volt through a resistance of one ohm.

Ampere Turns: A measure of the magnetizing or demagnetizing strength of the coil, which is the product of the number of turns in a coil and the number of amperes of current flowing through it.

Chemical Element: Any material that is composed of only one type of atom. It is also called a basic element or just an element.

Chemical Formula: A formula used to describe the types of atoms and their numbers in an element or compound.

Circuit: A closed path followed or capable of being followed by an electric current.

Circuit Diagrams: A type of diagram that is a pictorial way of showing circuits.

Circular Magnetism: The circular magnetic field around and inside a solid magnetic conductor when an electric current is passed through it.

Coil: More than one loop of a conductor wound in a spiral.

Conductivity: A measure of the ability of a material to conduct electrical current.

Conductors: Materials that have free electrons and allow electrical current to flow easily.

Corrosion: Deterioration of a metal by chemical or electrochemical reaction with its environment.

Coulomb: A charge that moves past a given point in one second. A coulomb is the charge carried by 6.25×10^{18} electrons.

Current (I): The flow of electrons, and measured in amperes.

Current Density: Current divided by the electrode area (current per unit area of the electrode)

Cycle (Hertz): One complete set of recurrent values of a periodic quantity comprises a cycle.

Defect: A discontinuity or other imperfection causing a reduction in the quality of a material or component.

Density: The mass of a substance per unit volume.

Depth of Penetration (Standard): The depth to which the eddy current density has decreased to 1/e or 36.8% of the surface density and also known as skin depth.

Detector: A device that determines the presence of or measures the amount of energy, such as radiation.

Eddy Currents: Circular induced currents that are generated by an alternating current in the nearby coil.

Eddy Current Inspection: An electromagnetic technique used on conductive materials for crack detection or the rapid sorting of small components for either flaws, size variations, or material variation, as well as other applications.

Eddy Current Method: An electromagnetic NDT Method based on the process of inducing electrical currents into a conductive material and observing the interaction between the currents and the material.

Eddy Current Testing (EC): An electromagnetic technique used on conductive materials for crack detection or the rapid sorting of small components for either flaws, size variations, or material variation, as well as other applications.

Electrochemical: Pertaining to combined electrical and chemical action. Deterioration (corrosion) of a metal occurs when an electrical current flows between cathodic and anodic areas on metal surfaces.

Electrochemical Corrosion: Corrosion which occurs when current flows between cathodic and anodic areas on metallic surfaces.

Electromagnet: Wrapping a wire into a coil creates an electromagnet, which behaves just like a regular permanent bar magnet when the current is flowing.

Electromagnetic Field: A field that is created when energy from a power source such as a battery is applied to a circuit, making the electrons flow through a conductor, a new type of field is developed around the wire.

Electromagnetic Induction: A process by which electrical current is induced in an electrical conductor by a changing magnetic field that acts upon the conductor.

Electromagnetic Testing: A nondestructive way to test materials by using electromagnetic energy.

Electromagnetism: The production of a magnetic field by current flowing in a conductor.

Electromagnets: An iron bar placed through the center of the coiled wire would become a temporary magnet, as long as the electric current is flowing through the wire.

Electromotive Force: The work or energy which causes the flow of an electric current. And it is expressed in volts. It should be noted that the term "force" is a misnomer. However, the term is so well established that its use continues in spite of its being incorrect.

Electron Volt: An amount of energy equal to the energy gained by one electron when it is accelerated by one volt,

Electron: A negatively charged particle that is in constant motion and generally orbits the nucleus of an atom. The electron is the lightest known particle that possesses a charge.

Faraday, Michael: A chemist in England during the early 1800's and is credited with the discovery of electromagnetic induction, electromagnetic rotations, the magneto-optical effect, diamagnetism, and many other discoveries.

Faraday's Law: The principle saying that whenever wires are moved with an electrical current, it creates a magnetic field.

Field Intensity: A term used to describe the strength of the electromagnetic field.

Flux Density: The number of flux lines per unit of area, measured at right angles to the direction of the flux. It is the measure of magnetic field strength.

Flux Leakage: Flux, or lines of force, leaking from pole to pole outside a magnet.

Fracture: A break, or separation, of a part into two or more pieces.

Frequency: The number of waves that pass a given point in a specified unit of time.

Hertz: One cycle per second.

Induced Current: Passing an alternating current through a conductor will set up a fluctuating magnetic field. If a second conductor in the form of a closed loop is placed in this field, the action of the fluctuating field moving across the conductor will set up a second alternating current of the same frequency. This is an induced current.

Induction: The process of generating current in a conductor by placing the conductor in a changing magnetic field.

Lenz's Law: An induced current has a direction such that its magnetic field opposes the change in magnetic field that induced the current.

Magnet: Any piece of iron, steel or magnetite that has the property of attracting iron or steel.

Magnetic Discontinuity: This refers to a break in the magnetic uniformity of the part-a sudden change in permeability. A magnetic discontinuity may not be related to any actual physical break in the metal, but it may produce a magnetic particle indication.

Magnetic Field: The space in which a magnetic force is exerted. This space exists within and around a magnetized material and a conductor carrying electrical current.

Magnetic Field Strength: The measured intensity of a magnetic field at a specific point. Usually expressed in amperes/meter

Magnetic Flux: A measure of quantity of magnetism, taking account of the strength and the extent of a magnetic field. The total number or lines of force existing in a magnetic circuit.

Magnetic Flux Density (B): The normal magnetic flux per unit area. Usually expressed in Tesla or Gauss.

Magnetic Lines of Force: Imaginary lines in the magnetic field indicating how strong the magnetic force is (the closer together the lines, the stronger the force).

Magnetic Loop: If a conductor carrying an electric current is bent in a loop, the magnetic lines of force enter on one side of space within the loop is found to contain a magnetic field which has very definite directional properties. Polarity is created within the coil with one end being a north pole and the opposite end a south pole. The space enclosed by the loops is longitudinally magnetized.

Magnetic Materials - Materials are affected by magnetism in two general ways. Some of them are attracted by a magnet, while others exert a repellent force. The first is called "paramagnetic" and the later "diamagnetic." In Magnetic particle inspection we are not ordinarily concerned with either of the two classes, but with what may be termed a subdivision of the first class called "ferromagnetic materials."

Magnetic Permeability: The ratio of the magnetic flux density, B, in a substance to the external field strength.

Magnetic Testing (MT): A nondestructive testing method used for defect detection.

Milliampere: Unit of electric current equal to one thousandth of an ampere.

NDE: Nondestructive Evaluation

NDT: Nondestructive Testing.

NDT Methods: A process used to test an object for flaws and other defects that does not harm the object.

Nondestructive Evaluation (NDE): The use of non-invasive techniques to determine the integrity of a material, component or structure, or to quantitatively measure some characteristic of an object.

Nondestructive Testing (NDT) - Testing to detect defects in materials using techniques that do not damage or destroy the items being tested.

Ohms: The unit used to measure resistance in electrical systems.

Ohm's Law: Electromotive force across a circuit is equal to the current

Permeability: The ease with which a magnetic flux can be established in a given magnetic circuit.

Permeability (Magnetic): Ratio between flux density, B, and magnetizing force, H. Permeability describes the intrinsic willingness of a material to conduct magnetic flux lines.

Propagation: Advancement of a wave through a medium.

Pulsed Eddy Current: A test used for detection and quantification of corrosion and cracking

Resistance (R): The opposition to the flow of electrical current. Measured in ohms

Resistivity: Reciprocal of conductivity.

Resistors: Components that are used to control that amount of current flowing in a circuit by adding a specific amount of resistance.

Transient Currents: These currents are of short duration, generated by sudden changed in the electrical or magnetic conditions existing in an electrical or magnetic circuit.

Volt (V): (1) The unit of electromotive force or potential difference that will cause a current of one ampere to flow through a conductor whose resistance is one ohm. (2) The unit of electromotive force or potential difference between two points when one joule of energy is used to move one coulomb of charge from one point to the other.

Voltage: Electromotive force or difference in electrical potential. Expressed in volts.

Voltmeter: The instrument used to measure voltage.

Calculations for I_{ind} in conducting loop:

As we know that the V_{emf} can be generated when there is a change in magnetic field with respect to time, as given in following formula.

$Vemf = -\int \frac{dB}{dt} ds$--- (1)

Where B=μH--- (2)

And $H = \frac{I}{A}$--- (3)

Putting equation (2) and (3) into equation (1) we get;

$Vemf = -\mu(I \times sin\omega t)(\frac{\pi d^2}{4})$--- (4)

Where $\omega = 2\pi f$

f=50 Hz, $\pi = 3.1415$ *, d=0.031m and* $\mu = 1.26 \times 10^{-6}$ *H/m*

Table (1): Current in metal plate

Voltage Supplied(V)	*Resistance (Ω)*	I_{plate} *(A)*
1	*2.03401*	*0.4916*
2	*2.03401*	*0.9832*
3	*2.03401*	*1.4749*
4	*2.03401*	*1.9665*
5	*2.03401*	*2.4581*

The resistance shown in table (1) is total resistance of plate and 2Ω resistor connected in series to the plate.

*The **H** in the plate can be calculated with the help of equation (3), and it is given in table (2).*

Table (2): Magnetic field in the metal plate

Voltage Supplied(V)	*Resistance (Ω)*	I_{plate} *(A)*	**H** *(A/m)*
1	*2.03401*	*0.4916*	*0.7909*
2	*2.03401*	*0.9832*	*1.5818*
3	*2.03401*	*1.4749*	*2.372*
4	*2.03401*	*1.9665*	*3.1633*
5	*2.03401*	*2.4581*	*3.9546*

*So putting the values of **I** from table (1) into equation (4), we get;*

Table (3): V_{ind} *in conducting loop*

Voltage Supplied(V)	*Resistance (Ω)*	I_{plate} *(A)*	V_{ind} *(μV)*
1	*2.03401*	*0.4916*	*3.3539*
2	*2.03401*	*0.9832*	*6.7078*
3	*2.03401*	*1.4749*	*10.062*
4	*2.03401*	*1.9665*	*13.416*
5	*2.03401*	*2.4581*	*16.770*

And current in the conducting loop can be calculated by dividing the coil resistance to voltage induced in the conducting loop. The results for current induced in conducting loop are given in table (4).

Table (4): Current induced in conducting loop

$V_{ind}\,(\mu V)$	$R_{coil}\,(\mu\Omega)$	$I_{ind}\,(\mu A)$
3.3539	2.6154	1.282
6.7078	2.6154	2.5647
10.062	2.6154	3.8472
13.416	2.6154	5.129
16.770	2.6154	6.142