LANDMINE DETECTION USING TMR SENSOR

A THESIS

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THESIS CERTIFICATE

This is to certify that the thesis entitled **"LANDMINE DETECTION USING TMR SENSOR"** submitted by **M V ARAVINDU** to the Indian Institute of Technology Madras for the award of the degree of **Master of Technology** is a bona fide record of research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Numerous countries suffer from the existence of millions of buried landmines in their territories. The use of landmine is controversial because of its indefinite life and potential as indiscriminate weapons which lasts even after the conflict ends. All mines contain some amount of metal and thus metal detectors are largely used for mine detection. The process of detecting and removing them is typically expensive, slow and dangerous. The main challenge for mine detection process is to increase positive detection and reduce false positives.

Contemporary technologies can be used effectively to improve the characteristics and capabilities of detection instruments. The project work includes study of metal detector technologies currently available and GMR and TMR technology. The high magnetic field sensitivity of TMR sensors can be a breakthrough in enhancing the performance of mine detectors. The objective of the work is to study the electromagnetic induction based mine detection technologies and to use TMR sensors to improve the detection capability.

The proposed scheme includes a magnetic coil as transmitter and a TMR sensor as receiver. The TMR sensor is placed at the centre of the transmitter coil. The coil is powered by impulse supplied by a capacitor charging-discharging circuit. The signal sensed by the TMR sensor is amplified, sampled and used for target detection. The metal target once placed in the vicinity of the transmitter produce an eddy-induced opposing field and varies the resultant field. This change in field can be sensed by the TMR sensor and is used for detection of metallic target. The sensor output without any metallic target in the vicinity is considered as the reference. The reference signal is then compared with sensor returns for any variation. The coil is made of 16 SWG copper wire with 30 turn and 10 cm radius. TMR sensor used is TLE 5501-E0001 manufactured by Infineon technologies. The sensor output is amplified and gathered using NI ELVIS II board and LabVIEW platform. The signals are visually analysed for target information by comparing with the reference signal. Observable variation is present in the signal with target placement in air. The scheme is implemented and experiments are conducted to assess the performance. The maximum detection range observed is 52 cm with a coil radius of 10 cm. The detection range and detection probability can be further improved by design enhancements such as coil shape optimisation and signal processing and detection circuits. Using multiple TMR sensors in a grid is also suggested for improvement of performance.

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ABBREVIATIONS

AT	Ampere Turns
BFO	Beat Frequency Oscillator
CPP	Current Perpendicular to Planes
ECS	Eddy Current Sensing
EIT	Electrical Impedance Tomography
GMR	Giant Magnetoresistance
GPR	Ground Penetrating Radar
IB	Induction Balance
IR	Infrared
MD	Metal Detector
MMWR	Millimeter Wave Radar
MOSFET	Metal Oxide Field Effect Transistor
MR	Magnetoresistance
MTJ	Magnetic Tunnel Junctions
NC	Normally Closed
PI	Pulse Induction
PLL	Phase Locked Loop
SNR	Signal to Noise Ratio
SPST	Single Pole Single Throw
SWG	Standard Wire Gauge
TMR	Tunnel Magnetoresistance
VCO	Voltage Controlled Oscillator

LIST OF SYMBOLS

μ_0	Permeability of free space
a	Radius of the coil
B	Magnetic flux intensity
I	Current
i	Instantaneous Current
I_D	Drain current
k	permanent resistance of circuit
L	Inductance
N	Number of turns of the coil
R	Resistance
r	Distance from centre of the coil
$R^{\uparrow\uparrow}$	Resistance in parallel state
$R^{\uparrow\downarrow}$	Resistance in antiparallel state
R_d	Damping Resistance
$R_{DS\ ON}$	Drain Source Resistance in ON state
R_{SW}	Switch Resistance
Rx	Receiver
t	Time
Tx	Transmitter
v	Instantaneous Voltage
V	Voltage
V_{IN}	Input Voltage
V_{REF}	Reference Voltage
V_{COIL}	Voltage across coil
V_{CTRL}	Switch control Voltage
z	Axial distance from the centre of the coil

CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

A land mine is an explosive device buried under or on the ground and designed to destroy or disable enemy targets, ranging from combatants to vehicles and tanks, as they pass over or near it. The use of land mines is controversial because of their potential as indiscriminate weapons. They can remain dangerous many years after a conflict has ended, harming civilians and the economy. 78 countries are contaminated with land mines and 15,000–20,000 people are killed every year while countless more are injured. Approximately 80% of land mine casualties are civilian, with children as the most affected age group.

Metal detectors were first used for demining, after its invention by the Polish engineer Józef Kosacki. His invention, known as the Polish mine detector, was used by the Allies alongside mechanical methods, to clear the German mine fields during the Second Battle of El Alamein in World War II. Whereas the placing and arming of mines is relatively inexpensive and simple, the process of detecting and removing them is typically expensive, slow, and dangerous. A great variety of methods for detecting landmines have been studied. These include electromagnetic methods like GPR (Ground Penetrating Radar) and BFO (Beat frequency Oscillator). Acoustic methods can sense the cavity created by mine casings. Sensors have been developed to detect vapour leaking from landmines. Animals such as rats and mongooses can safely move over a minefield and detect mines and can also be used to screen air samples over potential minefields. Bees, plants and bacteria are also potentially useful. Explosives in landmines can also be detected directly using nuclear quadrupole resonance and neutron probes. The casing of blast mines may be made of metal, wood or plastic. Some mines, referred to as minimum metal mines, are constructed with as little metal as possible to make them difficult to detect.

1.2. STATE OF THE ART

Although metal detectors have become much lighter, more sensitive and easier to operate than the early models, the basic principle is still electromagnetic induction. Current through a wire coil produces a time-varying magnetic field that in turn induces currents in conducting objects in the ground. In turn, these currents generate a magnetic field that induces currents in a receiver coil, and the resulting changes in electric potential can be used to detect metal objects. Nearly all mines contain enough metal to be detectable. No detector finds all mines, and the performance depends on factors such as the soil, type of mine and depth of burial. An international study in 2001 found that the most effective detector found 91 % of the test mines in clay soil but only 71 % in iron-rich soil. The worst detector found only 11 % even in clay soils. The results can be improved by multiple passes. An even greater problem is the number of false positives. Minefields contain many other fragments of metal, including shrapnel, bullet casings, and metallic minerals. 100–1000 such objects are found for every real mine. Greater the sensitivity more false-positives occurs. Universities, corporations and government bodies have been developing a great variety of methods for detecting mines. However, it is difficult to compare their performance. One quantitative measure is a Receiver Operating Characteristic (ROC) curve, which measures the trade-off between false positives and false negatives. Ideally, there should be a high probability of detection with few false positives, but such curves have not been obtained for most of the technologies.

Modern mine detectors are equipped for different terrain types and targets. Low metal content targets to large metal targets are detected in all soils and shallow water. Most of the modern mine detectors employ Advanced Pulse Induction Technology (APIT) for deep detection of targets. Major manufactures working in this field include Fisher Research Laboratory, Garrett Metal Detectors, Minelab, XP Metal Detectors, Nokta Metal Detectors, Tesoro Metal Detectors and Makro Metal Detectors.

1.3. OBJECTIVE OF THE WORK

1. To study the Electromagnetic Induction based technologies used for land mine detection and TMR and GMR sensor technology.
2. Device an instrument to detect buried landmine using TMR sensor.
3. Enhance detection range through design improvements.

1.4. MOTIVATION

Mine detection is a difficult and dangerous process. Modern technologies can be used effectively to improve the detection capabilities of instruments. The high magnetic field sensitivity of TMR sensors can be a revolution in improving the performance of mine detectors. This, in association with better signal analysis circuits can improve positive detection and reduce false detection.

CHAPTER 2

THEORETICAL ASPECTS OF THE WORK

2.1. INTRODUCTION

A common approach to detect a metal's proximity or analyse some characteristic of it in applications, such as proximity sensing, non-destructive evaluation, and so on, is to generate eddy currents in it and then extract the desired information from the features of these eddy currents using eddy current sensors (ECSs). Some of the common ECS are Hall-effect sensors and inductive coils. Lately, giant magneto-resistive (GMR) sensors are also used for ECS due to their higher sensitivity and better low-frequency response. Numerous techniques are available to detect buried landmines. The major focus of this project work is on metal detection using electromagnetic induction based detection principles and techniques. A brief description about landmines and its specification is presented first, followed by theoretical perspectives of different electromagnetic detection principle presently used. Giant magneto-resistance (GMR) and Tunnel Magneto-resistance (TMR) sensors are explained and a study on the impact of number of turns of the coil and its radius on the resultant magnetic field is also presented.

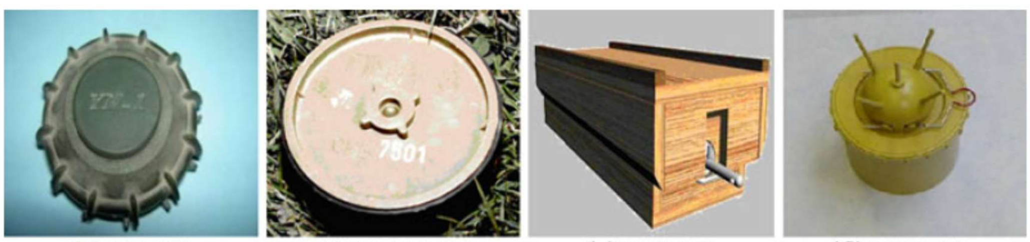
2.2. LANDMINES TYPES AND SPECIFICATIONS

Landmines can be classified according to their design to three main categories; blast, bounding and fragmentation landmines. Blast landmines are buried close to the surface of the soil and are generally triggered by pressure (e.g. driving over or stepping on them) or by handling/ disturbing. Pressure activated mines generally require approximately 5–16 kg of pressure to explode. The main purpose of these landmines is to destroy an object in close proximity, such as a person's foot or leg. Bounding Landmines are buried with only a small part of the initiator protruding from the ground. When activated, the initiator sets a propelling charge, lifting the mine about 1 m into the air in order to cause injury to a person's head and chest. Fragmentation Landmines release fragments in all directions or can be arranged to send fragments in one direction. These landmines can cause injuries up to 200 m away and kill at closer distances.

According to the potential target, there are two main types of buried landmines; AP (Anti-Personnel) landmines and AT(Anti-Tank) landmines. AT landmines are usually buried in roads or tracks, and designed to explode as a heavy vehicle passes over them. AP landmines are small devices that explode when stepped on or disturbed. Their main military purpose is to hurt enemy soldiers rather than killing them. Table 2.1 provides a brief comparison of AP and AT landmines.

(a) VS 1.6. (b) M15.

Fig. 2.1 AT Landmines



(a) VS 5.0. (b) PMA 3. (c) PMD 6. (d) VAL 69.

Fig. 2.2. AP Landmines

Table 2.1 Comparison between AT and AP landmines

Type	AP landmines	AT landmines
Weight	Light (100 g–4 kg)	Heavy (6 kg–11 kg)
Size (diameter)	6–20 cm	20–50 cm
Target	Human	Vehicle
Case material	Plastic, metal, wood	Plastic, metal
Operating pressure	500 g	120 kg

2.3. ELECTROMAGNETIC DETECTION

Landmine detection using electromagnetic radiation is based on the difference between the electromagnetic properties of the target and the ground. Several versions of the electromagnetic techniques are currently employed or envisioned to detect buried landmines. These versions typically differ in the operating frequency, the employed bandwidth of the electromagnetic spectrum, the type of the transmitted signals, the interpretation of the reflected signals, or the type of transmitter and receiver. Metal detector (MD), ground penetrating radar (GPR), microwave radar (MWR), millimetre wave radar (MMWR), electrical impedance tomography (EIT) and infrared (IR) techniques are common electromagnetic detection techniques. They are briefly explained below.

2.3.1. Metal Detector (MD)

The metal detector technique is based on electromagnetic induction. It is composed of a primary coil (transmitter) and one or more secondary coils (receiver). In some arrangements, a single coil is actually sufficient. A time-varying current in the transmitter coil generates an electromagnetic field, which induces electric (eddy) currents in nearby metallic objects. These eddy currents, in turn, induce a time varying current in the receiver coil, which is amplified and processed to provide an indication for the presence of landmines. The main advantage of this technique is its ability to detect metal objects of dimensions less than 1 cm at a depth of 50 cm. It has low cost, and it is reliable in all weather and soil moisture conditions. A drawback is that it cannot detect landmines with a small metal content such as the modern plastic landmines. It cannot discriminate between landmines and metal debris, which causes high false alarm rates.

2.3.2 Ground Penetrating Radar (GPR)

The GPR detection operates by transmitting an electromagnetic signal into the soil and detecting the reflected signal at the receiver. The transmitter emits a pulsed wave or a continuous wave with a given frequency. The receiver collects the waves backscattered by the discontinuities in permittivity. Discontinuities can be caused by both the buried objects like landmines (useful signal) and the natural discontinuities in the soil (clutter). The main advantage of this technique is its ability to detect plastic objects buried in the ground; as a result, it can be used to find landmines with different types of casing. It can also provide information about the target depth. It is rather insensitive to small metallic debris. Microwaves are strongly attenuated by certain types of conductive soils such as clay, so wet clay in particular provides an extremely challenging environment. Very dry soils have a reduced electrical contrast, when compared to the plastic cased landmines and therefore these types of landmines may not be detected.

2.3.3 Microwave Radar

This technique is based on the transmission of short radio and microwaves radiation pulses from an antenna into the ground and measuring the time for reflections to return to the same antenna. Reflections occur at the boundaries between materials of different dielectric constants that are normal to the incident radiation. Transmitting high frequencies provides high resolution images, but it is subject to high attenuation in the soil. Thus, high frequencies are suitable for the detection of small shallow objects. Conversely, low frequencies achieve lower resolutions but are less attenuated in the soil. Hence, they are more suitable for detecting large and deep objects. In this technique, the detection depth depends strongly on the operating frequency, the soil humidity and conductivity, and the landmine case and size. The best detection results are likely to be obtained for large metallic objects in dry soils. This technique is less effective in wet soils, and it has to be protected from radio frequency interference.

2.3.4. Millimetre Wave Radar (MMWR)

It is a hyperspectral system that collects images at different MMW frequencies (from 90 to 140 GHz) using a vector network analyser that collects backscattering MMW radiation from the buried sample. The best results are obtained in dry soils. The millimetre waves can penetrate through cloud, smoke, dust, dry leaves and thin layers of the dry soil and offer different thermal contrasts of objects providing different views of the target scene. This technique has some limitations; the emissions are typically much weaker than IR emissions, and the MMW signatures take longer times to collect and process and require larger aperture collection devices.

2.3.5. Electrical Impedance Tomography (EIT)

This method uses electrical currents to produce a conductivity image of an area being investigated for landmines. Some electrodes are placed around the edge of the area and then combinations of the electrodes are stimulated in sequence to produce the electrical conductivity contour map. As both metallic and plastic landmines have different conductivities from that of the soil, they appear on the map and can be removed. The main advantage of this method is its suitability to wet lands and underwater applications. The EIT sensor head is cheap enough to be disposable and remotely inserted to improve safety. This technique is appropriate for detecting all types of landmines, and the equipment used is relatively simple and inexpensive. The limitation of this method is the required physical contact with the ground, which may detonate the landmine. This method cannot be used with a dry soil. It is also sensitive to electrical noise.

2.3.6. Infrared (IR)

The concept of using IR thermography for landmine detection is based on the fact that the landmines might have different thermal properties from the surrounding materials. This technique is safe, uses lightweight equipment, and can scan large areas. It does not need too much pre-processing; it can work by accepting only the natural radiation from the object or it can provide an extra heat source and receive the artificial radiation created by that heat source. The performance of the IR technique relies highly on the environment at the moment of measurement. It can be affected by factors like the weather conditions, the time of the day, and the background environment.

2.4. METAL DETECTORS

There are several ways to categorize metal detector types. Based on its principle of working the common techniques are Frequency shift, Induction Balance and Pulse Induction.

2.4.1. Frequency shift

Frequency shift detectors are usually characterized by having a single loop in the search head that oscillates at a particular frequency, and in which targets cause a measurable shift in that frequency. The most popular frequency shift design is the beat-frequency oscillator (BFO). Off-resonance and Phase Locked Loop (PLL) are other methods of frequency shift metal detection.

The block diagram of BFO type detector is given in figure 2.3. BFO designs consist of two radio frequency (RF) oscillators, usually oscillating at a frequency of around 100 kHz. One of the oscillators incorporates the search coil, and the second oscillator uses a much smaller coil that is hidden inside the control box, and is known as the reference oscillator. The two oscillators are adjusted so that their frequencies are nearly the same, and their outputs are summed (or mixed) to produce sum and difference frequencies. The sum of the two frequencies is filtered out by the electronics leaving the difference signal which conveniently lies within the audio band of 20 Hz to 20 kHz. When a metal object is brought close to the search coil it affects the inductance value of the coil and the oscillator frequency is altered slightly, and this in turn affects the difference in frequency. The user would hear a change in audio tone signifying the presence of a metal target.

BFO type detectors are prone to drift (small changes in component values) as the temperature changes, which requires the user to frequently retune the fixed oscillator. Since most BFOs operate at a relatively high frequency of 100 kHz they tend to be affected by ground capacitance. This means that simply bringing the search coil close to the ground can cause a decrease in the difference frequency. The higher the frequency of the search oscillator the more susceptible it will be to ground effects.

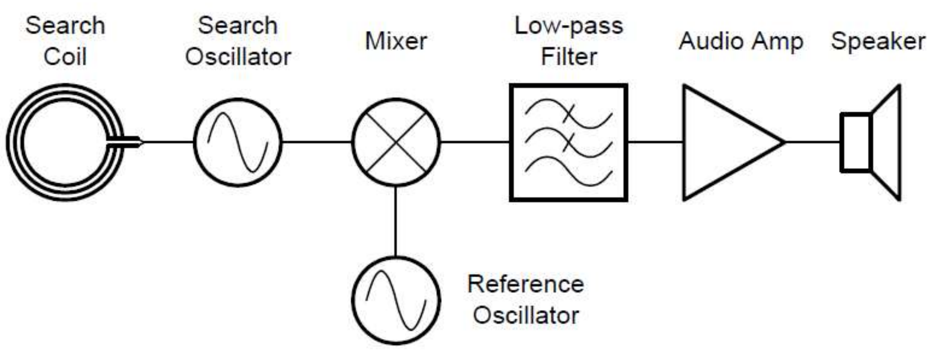


Fig 2.3. Block diagram of BFO type metal detector

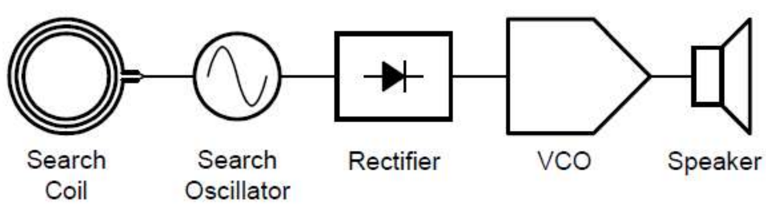


Fig 2.4. Block diagram of off resonance type metal detector

Figure 2.4 shows the block diagram of Off-resonance type metal detector. An oscillator is used to drive the search coil (similar to the BFO) but via a high resistance, and the output voltage is rectified before being applied to the input of a comparator, where it is compared to a reference voltage. The rectifier output is applied directly to the input of a voltage-controlled oscillator (VCO) so that the operator can effectively “hear” the change in inductance caused by the presence of a metal target. This method has the advantage of providing some elementary ferrous/ non-ferrous discrimination.

2.4.2. Induction Balance (IB)

IB designs use a search head that contains both a transmit (Tx) coil for transmitting a continuous waveform (usually a sinusoid) and a receive (Rx) coil for receiving target signals. Transmitter coil is driven by the oscillator and the Receiver coil is used to pick up signals from the first. These two coils are positioned in an overlapping fashion so that one coil is very loosely coupled to the other. There is very little mutual inductance between the coils and therefore very little transmit signal gets directly coupled to the receive coil.

The figure 2.5 illustrates the induction balance principle. Since the magnetic field on the outside of the primary coil is opposite in direction to the interior field, there will be some cancellation in field coupling to the secondary coil. As we continue to slide the secondary coil over, at some point there will be a position where the interior and exterior fields exactly cancel, and there will be no coupling between the primary and secondary coils. This state is called induction balance. When a metal target is in close proximity to the search head, the magnetic field pattern of the transmit coil is disturbed, and thus the coupling between the transmit and receive coils will be increased.

This technique is far more sensitive than the BFO type of detector, but it has the disadvantage that careful alignment of the coils is required. The 'Transmit-Receive metal detectors' and 'VLF metal detectors' belongs to this category.

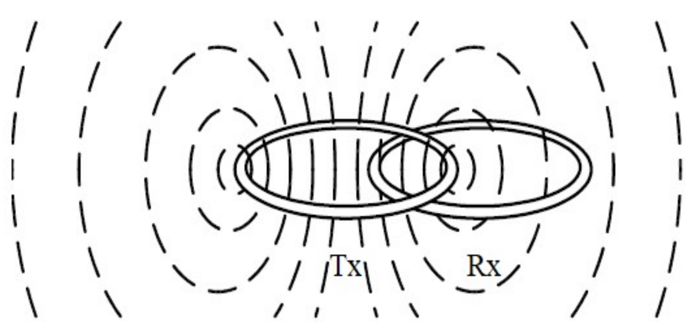


Fig 2.5. Induction balanced coils

2.4.3. Pulse Induction (PI)

PI metal detector works by transmitting a rapid impulse, then switching to receive mode and listening to the impulse response. It is possible to use separate transmit and receiver coils for this and they can be induction balanced, or a single coil like BFO. A major difference is that the PI detector transmits an impulse train, not a continuous-time waveform. The coil is briefly energized with a DC current which produces a static magnetic field, then the current is quickly shut off which collapses the magnetic field. The higher the coil current and the faster it is shut off, the higher the magnetic field transient dB/dt will be. The faster the magnetic field changes, the greater will be the induced eddy current *i*:

$$i = -\ \frac{1}{R} * \frac{dB}{dt} \tag{2.1}$$

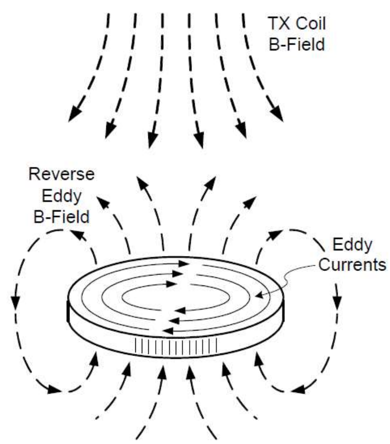


Fig 2.6. Eddy current generation on metallic surface

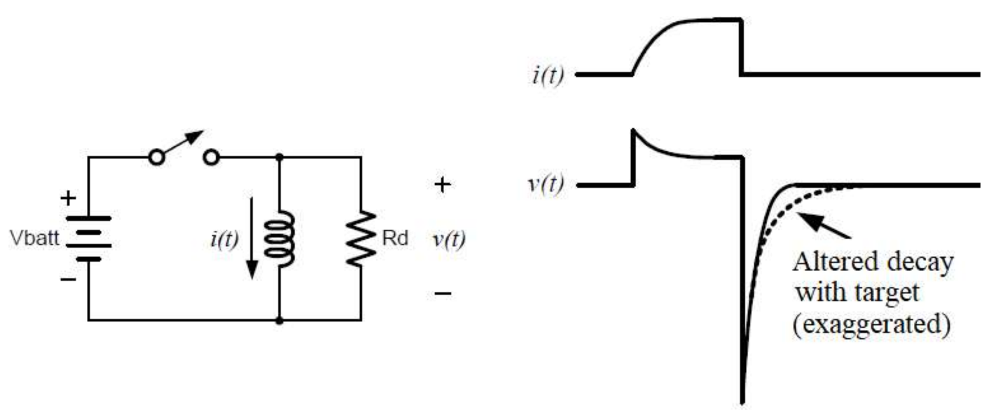
Figure 2.7.(a) depicts the circuit schematic for pulse induction. When the switch is closed, the battery is connected directly across the coil. As the switch closes the coil current does not immediately jump up to a DC level, but exponentially builds up to a peak value, following a classic RL response determined by the inductance of the coil, the non-ideal series resistances of the coil, the switch and the battery. At the same time, the coil voltage initially jumps up to the same value as the battery, but then exponentially decays to some lower level determined by the resistances of the coil.

When the switch is opened, the current suddenly drops to zero, and collapses the magnetic field creating a high dB/dt. It so happens that, because the coil is a simple inductor with inductance L, and resist sudden changes in current, the high-slewing current at turn-off also generates a large voltage spike '*v*' across the coil.

$$v = L\,dI/dt \tag{2.2}$$

This is called the "fly-back" voltage. For an ideal inductor, the fly-back voltage is an instantaneous spike that ends abruptly when the coil current reaches zero. Although an ideal inductor has an instantaneous spike, a real inductor is far more complicated, and has series wire resistance, plus capacitance between windings. A damping resistor (R_d) is added in parallel with the coil to get rid of the ringing and provide a nice, smooth exponential response.

While the charging current follows an exponential curve set by the inductance and total series resistance, the fly-back exponential follows an exponential response determined by the inductance and parallel damping resistor. When the coil is turned off, the magnetic field collapses in a fast transient dB/dt. This magnetic transient induces eddy currents in a metal target. From the sudden dB/dt, the induced eddy currents jump to some value, and then they also decay exponentially, with a time constant determined by the electrical characteristics of the target. The counter-magnetic field of the eddy currents follows this decay, and this counter-magnetic field alters the fly-back decay (dotted lines) as shown in figure 2.7.(b). In other words, in the absence of a target, the fly-back decay is determined by only the coil and damping resistor. But when a target is present, the fly-back decay is altered by the counter-magnetic field, which decays with the time constant of the target. We can monitor the fly-back decay and determine the presence of a target. The altered decay shown in Figure 2.7.(b) is greatly exaggerated; in reality, the decay shift caused by targets will be in the microvolts to millivolts range.



(a) (b)

Fig 2.7. (a) Switched coil with damper. (b) Current and voltage waveforms

2.5. GMR AND TMR SENSOR TECHNOLOGY

Magnetoresistance (MR) is the dependence of the electrical resistance of a sample on the strength of an external magnetic field. Figure 2.8 depicts the concept of MR with magnetic field. Numerically, it is characterized by the value MR ratio;

$$MR = \frac{R^{\uparrow\downarrow} - R^{\uparrow\uparrow}}{R^{\uparrow\uparrow}} \tag{2.3}$$

Where;

MR is the so-called magnetoresistance level or ratio.

$R^{\uparrow\downarrow}$ is the (maximum) resistance in the anti-parallel state.

$R^{\uparrow\uparrow}$ is the (minimum) resistance in the parallel state.

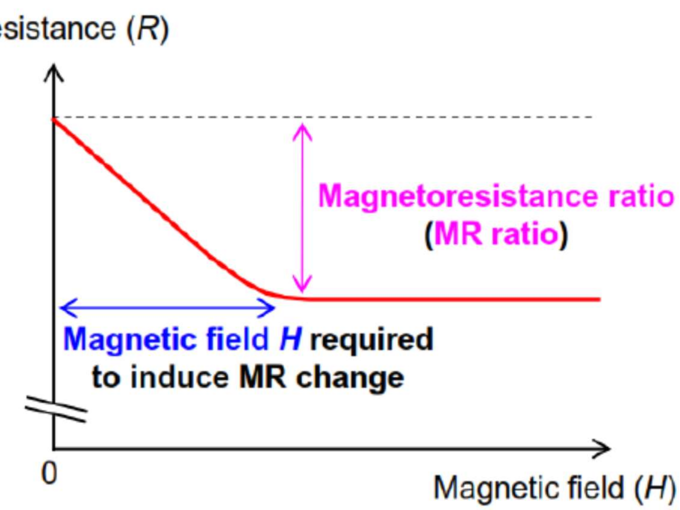


Fig. 2.8. Change in resistance to magnetic field intensity

Giant magnetoresistance (GMR) is a quantum mechanical magnetoresistance effect observed in multilayers composed of alternating ferromagnetic and non-magnetic conductive layers. The effect is observed as a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers is in a parallel or an antiparallel alignment. The overall resistance is relatively low for parallel alignment ($R^{\uparrow\uparrow}$) and relatively high for antiparallel alignment ($R^{\uparrow\downarrow}$). The magnetization direction can be controlled, for example, by applying an external magnetic field. The effect is based on the dependence of electron scattering on the spin orientation. The main application of GMR is magnetic field sensors, which are used to read data in hard disk drives, biosensors, microelectromechanical systems and other devices. GMR multilayer structures are also used in magneto-resistive random-access memory as cells that store one bit of information. The MR for GMR sensors is approximately 5% to 15%.

Magnetic tunnel junctions (MTJ), also called Tunnel Magnetoresistance (TMR) structures, were initially described as GMR structures. Nowadays, they are considered a specific MR effect. In this case, the magnetic layers are separated not by a conductive layer but by a very thin isolating layer, following a current perpendicular to planes (CPP) configuration. Electrons can cross this thin film by means of the quantum tunnel effect. As deduced from quantum mechanics arguments, the crossing probability is higher when both magnetic moments are aligned in parallel and lower when both magnetic moments are not aligned in parallel. Typical MR levels of MTJ are above 40%, with Al_2O_3 as the isolating layer. Recently, MR levels of about 200% have been reported for MgO based structures. Figure 2.9 depicts the TMR and GMR structures with magnetisation and current direction.

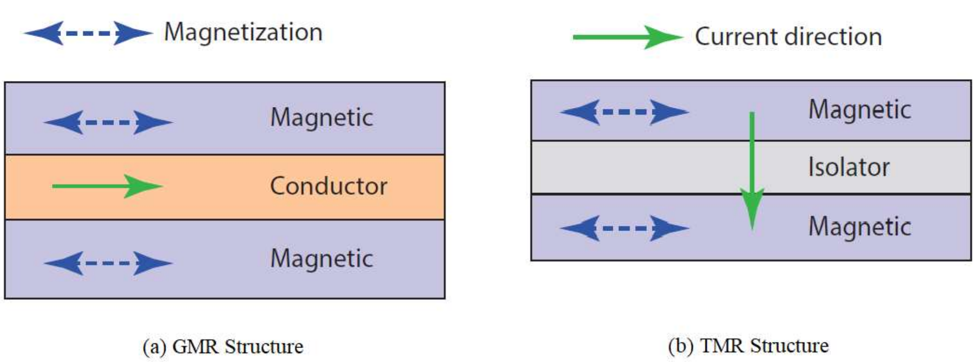


Fig. 2.9. (a) GMR structure and (b) TMR structure

The intrinsically useful range of MR-based sensors is mainly limited by two mechanisms. At the low-level region, the SNR sets the detection limit. At the high signal region, the saturation field is the limitation mechanism. GMR/ TMR can be applied in the range from some picotesles (pT) to almost kilotesles (kT), which is more than 14 orders of magnitude much better compared with other magnetic sensors.

2.6. TMR IC TLE 5501-E0001

The TLE 5501 is a tunnel magnetoresistance-based, 360° angle sensor that detects the orientation of a magnetic field, manufactured by Infineon technologies. It is achieved by measuring sine and cosine angle components with Tunnelling Magneto Resistance (TMR) elements. These raw signals (sine and cosine) are provided as a differential output signal and can directly be further processed with a micro controller.

The TLE5501 consists of 8 TMR elements, which are arranged in 2 Wheatstone bridges. The resistance of these resistors depends on the direction of the external magnetic field. Each bridge provides a differential output signal, i.e. X (cosine) and Y (sine) signals which can further be processed for angle calculation. Figure 2.10 illustrates the block diagram of TLE 5501-E0001.

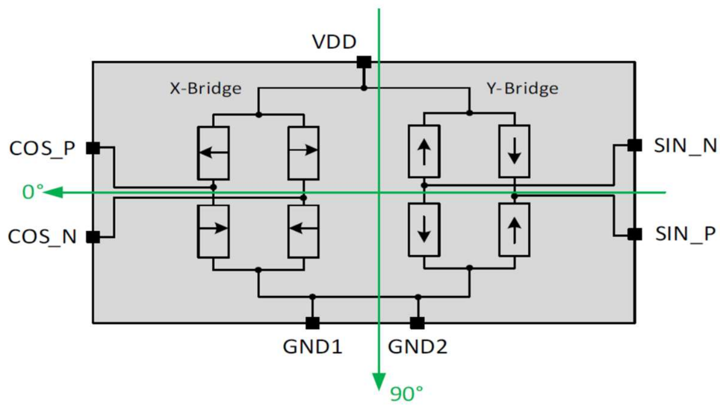


Fig. 2.10. Block Diagram of TLE 5501-E0001.

The tables given below (table 2.2, table 2.3 and table 2.4) gives the details about pin details, operating range and the electrical characteristics of TMR IC TLE 5501.

Table 2.2. Pin details TLE 5501-E0001.

Pin No.	Symbol	In/Out	Function
1	COS_P	O	Analog positive cosine output
2	COS_N	O	Analog negative cosine output
3	GND2	I	Ground, internally connected to GND1
4	GND1	I	Ground
5	n.c		not used, internally connected to GND2
6	VDD	I	Supply voltage
7	SIN_N	O	Analog negative sine output
8	SIN_P	O	Analog positive sine output

Table 2.3. Operating range of TLE 5501

Parameter	Symbol	Values			Unit
		Min.	Typ.	Max.	
Operating supply voltage	V_{DD}	2.7	–	5.5	V
Operating ambient temperature	T_A	-40	–	150	°C
Angle speed	n	–	–	1E6	°/s
Magnetic field range	B	20	–	100	mT
Extended magnetic field range	$B_{extended}$	20	–	130	mT

Table 2.4. Electrical parameters of TLE 5501

Parameter	Symbol	Values			Unit
		Min.	Typ.	Max.	
Bridge resistance	R_{bridge}	4000	6000	8000	Ohm
Temperature coefficient of bridge resistance	TC_{bridge}	-0.124	-0.1	0	%/K
Differential output voltage amplitude	$A_{out,diff}$	270	320	370	mV/V
Single ended output voltage amplitude	$A_{out,se}$	135	160	185	mV/V
Supply current	I_S	–	1.67	2.5	mA

2.7. MAGNETIC FIELD PRODUCED BY A COIL

A wire or coil that is carrying a current produces a magnetic field B. The strength of the field B is proportional to the current I in the coil. The strength and direction of the field at distance r from the centre of the coil depend on length and shape of wire and distance r. For large distances from the coil (r >> a, where a is the radius of the coil) the shape of the magnetic field of a coil is identical to the electric field produced by a point electric dipole. The direction of the field is given by the 'right hand rule', where the fingers curl around the coil in the direction of the current and the extended thumb points in the direction of the field. Field at the central region is comparatively strong and uniform. Just outside the coil, the field is produced mainly by the closest portion of the wire. The current from the far side of the coil contributes relatively little, due to its greater distance from the source. Except along the axis, the magnetic field of a circular coil cannot be expressed in closed form. Along the coil axis, if the origin of the coordinates is taken at the centre of the coil and if the z axis is taken along the coil axis, the magnitude of the magnetic field B, which points in the z direction, is given by;

$$B = \frac{\mu_0 N a^2 I}{2(a^2 + z^2)^{(3/2)}} \tag{2.4}$$

where B is in tesla if

μ_0 is 4 x 10^{-7} is the vacuum permeability,

N is the number of turns of the coil,

I is the current in the wire in amperes,

a is the radius of the coil in meters, and

z is the axial distance in meters from the centre of the coil.

From the above equation, it is evident that for large distances, fields fall off as $1/r^3$ or $1/z^3$. The variation of magnetic field (B) with varying axial distances is shown in figure 2.11 below for different coil radius. It can be observed that for distances much more than the coil radius, the field increase with radius, but at the centre of the coil and points nearer to it, the field decrease with increase in coil radius.

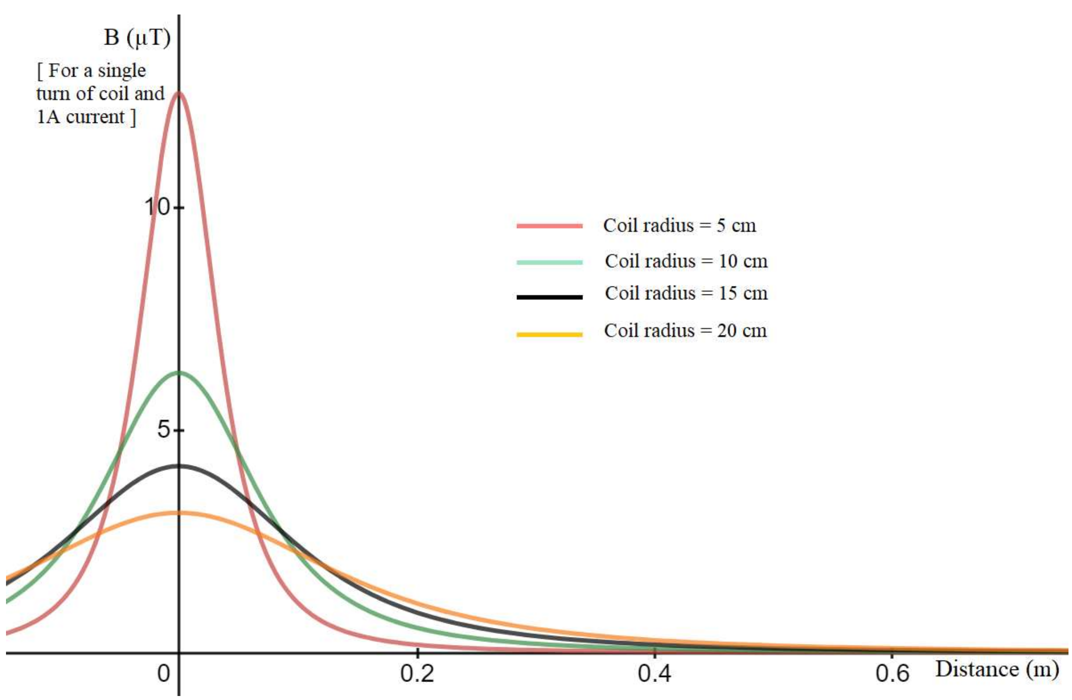


Fig. 2.11. Variation of Magnetic field with axial distance from the centre of coil, for 1A current through one turn.

The variation of magnetic field (B) at certain distances is shown in figure 2.12 below for varying coil radius. It can be observed that for a particular axial distance the field can be kept maximum by adjusting the coil radius. For instance, to maximize field at an axial distance of 20 cm the radius of the coil can be 28 cm.

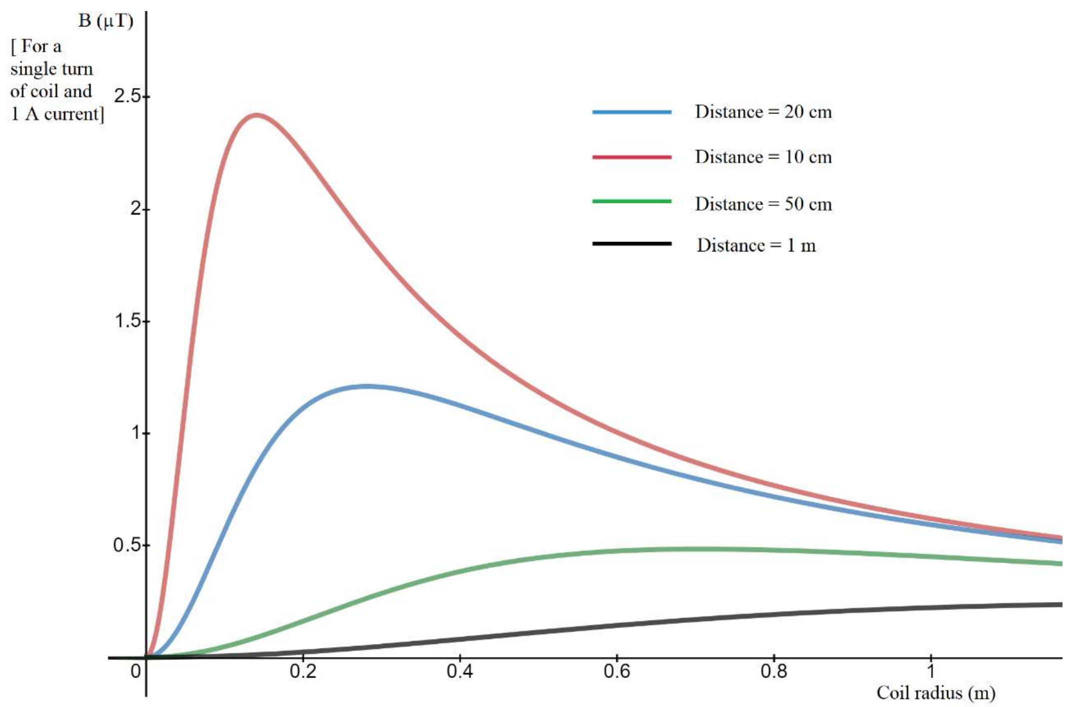


Fig. 2.12. Variation of Magnetic field at axial distances, with variation of coil radius coil, for 1A current through one turn.

Increasing the number of turns of the coil without varying the coil radius theoretically will not make any difference in magnetic field, since increasing the number of turns in result will proportionally increase the coil resistance and reduce the current through it. Assume The coil 'x' with N turns and current I with and connected to a voltage source of voltage V. Let the resistance of coil 'x' per turn be R. Then;

Magnetic Field, $B \,\alpha\, NI$ (2.5)

$I \,\alpha\, 1 / NR$ (2.6)

If the turns of the coil are increased β times to Nβ, then coil resistance also increases to RNβ. The resultant magnetic, B_β field will be;

$$B_\beta \;\alpha\; N\beta \times 1 / NR\beta \qquad (2.7)$$

B_β α NI or B α 1/R ; which is same as previous coil and is independent of number of turns N, i.e $B = B_\beta$.

But in practical cases there will be certain permanent resistance in the circuit due to switch and contact resistances, not dependent on the number of turns of the coil. By introducing a small but permanent resistance 'k' in the previous example; the circuit resistance with coil of N turns will be NR + k where R is the resistance per turn.

So current in the coil N; $I \;\alpha\; 1 / (NR+k)$ and $B \;\alpha\; N / (NR+k)$ (2.8)

And for coil of Nβ turns; $I_\beta \;\alpha\; 1 / (NR\beta+k)$ and $B_\beta \;\alpha\; N\beta / (NR\beta+k)$ (2.9)

Which means that $B \neq B_\beta$ with circuit resistance.

The graph plotted below at figure 2.13 shows the change in ampere turns (AT) with variation in number of turns in the coil (N) with a small permanent resistance (k) in the circuit at constant source voltage. From the graph it is clear that increasing the cable diameter (wire gauge) improves current as the number of turns increases. Moreover, with increase in coil diameter resultant AT reduces.

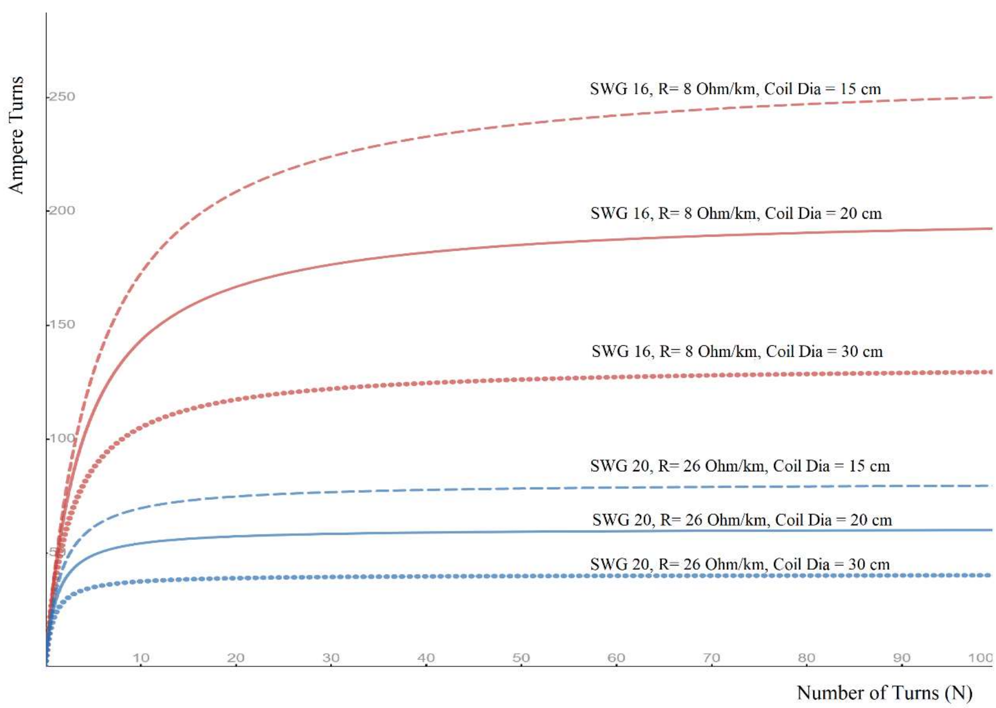


Fig. 2.13. Ampereturns (AT) Vs number of turns(N) for various coil diameter and wire gauge. Circuit resistance (k) is assumed to be 20 mΩ and source of 1V.

The relation of ampere turns (AT), number of turns (N), constant resistance of circuit (k), supply voltage (V) and resistance of the wire per turn (R) can be expressed as follows;

$$AT = \frac{NV}{\mathrm{k} + N\mathrm{R}} \tag{2.10}$$

And

$$AT_{max} = \frac{V}{\mathrm{R}} \tag{2.11}$$

The graph below in figure 2.14 depicts the variation of Ampere Turns (AT) with number of turs (N) for different values of circuit resistance 'k'. With lower values of 'k' better ampere turns can be achieved with relatively small number of coils turns.

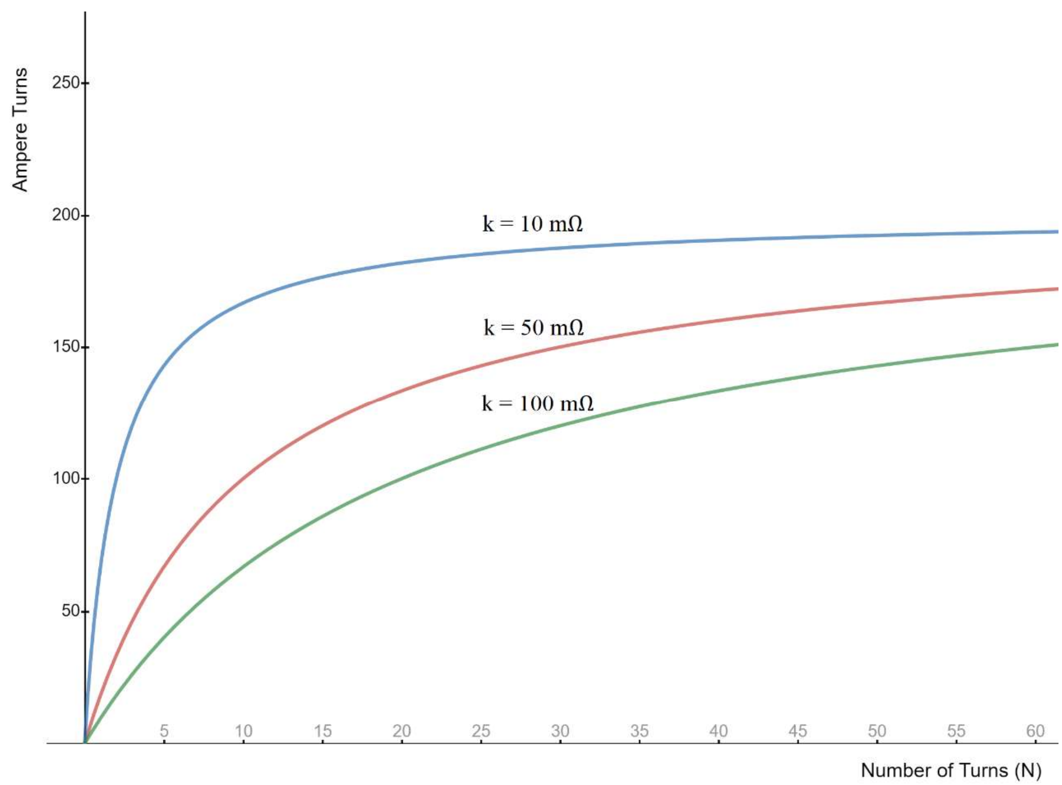


Fig. 2.14. Ampere turns (AT) Vs Number of turns(N) for various values of constant circuit resistance (k). Coil is assumed to be of a radius 10 cm, made of 16 SWG wire and source of 1V.

2.8. PROPOSED SCHEME

Various principles and methods used for landmine detections are discussed in above sections. The new generation technologies like TMR and GMR are also mentioned briefly. The proposed method of landmine detection is a combination of the above-mentioned principles and techniques.

The detection instrument involves a transmitter, receiver and a signal processing and detection circuit. The transmitter is meant for producing impulse magnetic fields of high amplitude. The receiver is a TMR sensor which essentially a magnetic sensor which is highly sensitive to small magnetic fields. The TMR sensor is placed at the centre of the transmitter coil. The signal sensed by the TMR sensor is amplified, sampled and used for target detection. The metal target once placed in the vicinity of the transmitter produce an eddy induced opposing field and varies the resultant field. This change in field can be sensed by the TMR sensor and is used for detection of target. The figure 2.15 shows block diagram representation of the proposed scheme.

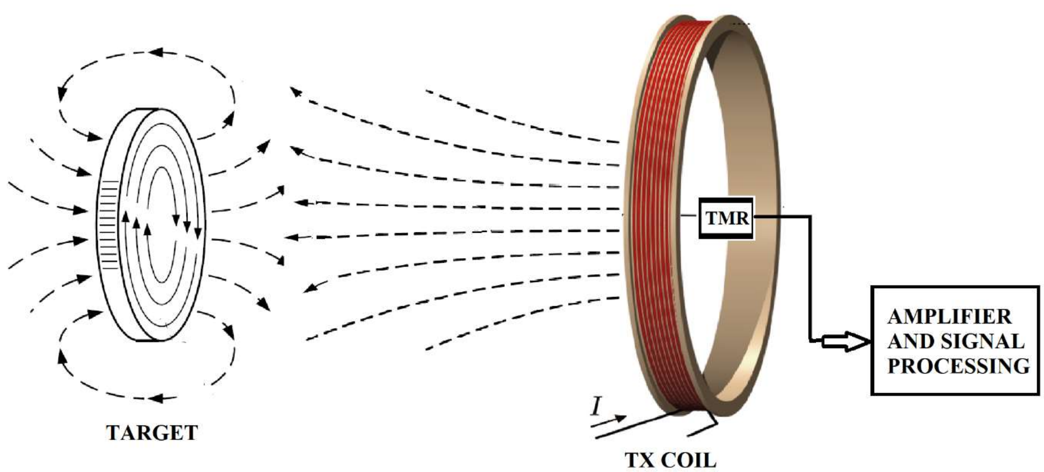


Fig 2.15. Block diagram of the proposed metal detector

The transmitter is similar to the Pulse Induction (PI) detector mentioned in section 2.4.3 in principle. The impulse train is generated by a clock-controlled capacitor charge-discharge circuit. The magnitude of the resultant field is decided by the capacitor charging voltage and circuit impedance. To ensure the maximum depth for detection the field has to be maximum possible. The graph in figure 2.11 and figure 2.12 depicts the manner in which magnetic field reduces with distance. It reduces almost $1/z^3$ times, z being the axial distance from the centre of the coil. The circuit resistance, which include the coil resistance and the switching circuit, has to be minimum for maximum current. A power MOSFET switch with very low ON mode-resistance can be employed as a switch in capacitor discharge circuit. A low resistance coil with maximum possible turns can effectively produce a higher ampere-turns (AT). An optimum number of turns can be found out from the graph in figure 2.13 and figure 2.14 and which compensates for switching circuit resistance.

Assume switch resistance (R_{SW}) of MOSFET switch as 20 mΩ ($R_{DS\ ON}$) and the coil is made of 16 SWG wire (8mΩ /m resistance). The capacitor is charged to a peak voltage of 25V (DC Supply, V). The maximum current that can be passed through the coil depends on the total resistance of the circuit which includes the resistance of switch and the coil. Let 'N' be the number of turns of the coil and 'R' the resistance per turn. Assume the coil radius 'a' to be 10 cm, and then the value of 'R' will be 5 mΩ. The total resistance will be 20 + 5N mΩ. The maximum ampere turns that can be achieved with the circuit is 5000 AT with zero switching circuit resistance. But practically it is not possible to achieve this. With switching resistance 20 mΩ, 80% of the maximum ampere turns (4000 AT) can be achieved with 16 turns and 50% with 4 turns. Let us assume 30 turns for the transmitter which results in 4412 AT. From equation 2.2 the magnetic field at the centre of the coil and at an axial distance 'z' can be calculated. The field at the centre of the coil will be 27.72 mT and at a distance (axial) of 50 cm will be 0.21 mT.

The TMR sensor can be placed at the centre of the coil to sense the change in the magnetic field. The alignment can be kept as parallel and perpendicular to the coil plane to sense the change in field. The output of the sensor can be taken from one arm or as a differential output of two different arms. The sensor output will vary with and without a metal target in the vicinity. A reference signal can be recorded without any target. The reference can then be compared with further sensor outputs to find out any variations. Any variation of sensor output from the reference can be assumed as a positive detection. The possibility of detection varies with the distance of the target distance and target size and type. Generally, the probability of positive detection increases, with decrease in distance and increase in target size. The conductivity of the target material also affects the probability as it affects the amplitude of eddy current.

CHAPTER 3

SCHEME IMPLEMENTATION

The metal detector is implemented in different configurations to compare the advantages and disadvantages. Experiments are conducted with different sensor circuit arrangements and target positions. The metal detection system mainly includes three parts; the transmitter, sensing circuit and the signal processing and detection unit.

The transmitter is essentially a coil which is actuated by current impulses. The coil produces impulsive magnetic field which interacts with the metallic targets. The transmitted magnetic field interacts with the metal target. This results in eddy currents on the metal target surface and results in an opposing magnetic field. Presence of the metal target causes changes in the resultant field which get captured by the TMR sensor. The TMR sensor is placed at the centre of the coil in both parallel and perpendicular directions one by one. The amplified output of the TMR sensor is captured using NI ELVIS II board and analysed for target information.

3.1.TRANSMITTER

The transmitter includes the coil and the circuit used to power it. The figure 3.1 shows the schematic of the coil and switching circuit. The specifications used are as follows;

(a) Switch S_1 : 5 V relay switch
(b) MOSFET Q1 : IRFZN44
    V_{DSS} : 55V
    $R_{DS\,ON}$: 17.5 mΩ
    I_D : 49A
(c) Charging resistance R_1: 50 Ω
(d) Capacitor : 50V, 1.1 mF
(e) Switch control signal : 10V, 2 Hz, Square wave, 10% Duty cycle
(f) DC Voltage : 27 V DC
(g) Coil Inductance: : 50 µH
    Resistance : 200 mΩ
    Turns : 30
    Wire Gauge : 16 SWG
    Shape : Circular
    Radius : 10 cm

(h) Fly-back diode D_1 : IN4001

The coil is energized by current impulses from a capacitor switching circuit. The figure 3.1 depicts the capacitor switching circuit along with the coil L_1.

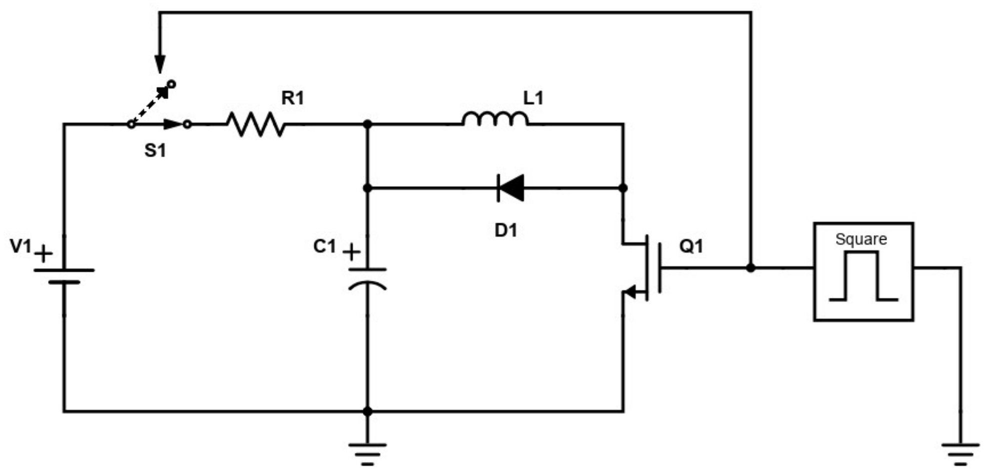


Fig 3.1. Transmitter schematic diagram

The capacitor C_1 is charged through a resistor R_1 by a constant voltage DC source V_1. Capacitor charging takes place when the SPST relay switch (NC) S_1 is in closed position. Capacitor discharge circuit is through the low resistance search coil $L_1$of metal detector switched by a power NMOSFET Q_1. The MOSFET Q_1 and capacitor charging switch S_1 are controlled by the same square wave signal source. When the square wave voltage is low S_1 conducts but MOSFET Q_1 open the circuit and vice versa. This results in charging the capacitor during LOW and discharging during HIGH period of square wave. The low resistance discharge path creates an electric impulse in the search coil which in turn creates an impulse magnetic field. The power MOSFET is suitable for smooth switching and low resistance ($R_{DS\ ON} < 20\ m\Omega$) circuit. The square wave signal is produced using the signal generator in NI ELVIS II board during the experiment.

3.2.RECEIVER

The receiver is the TMR sensor whose output is amplified by an instrument amplifier. The transmitted magnetic field interacts with the metal target. This results in eddy currents on the target surface and results in an opposing magnetic field. Presence of the metal target causes changes in the resultant field which get captured by the TMR sensor. Two configurations of receiver arrangements are experimented. Configuration-I and Configuration-II are shown in figures 3.2 and figure 3.3 respectively. The specifications of configuration-I are as follows;

(a) TMR Sensor : TLE 5501-E0001 (Only positive cosine output, pin 1)
(b) Resistors R1, R2, R3, R6 : 100 kΩ, 100 kΩ, 1 kΩ Pot, 100 kΩ
(c) Capacitor : 10 µF
(d) Amplifier : AD 620
(e) Gain : 150
(f) TMR IC location : Placed radially at the centre of the coil.
(g) DC supply : 5V

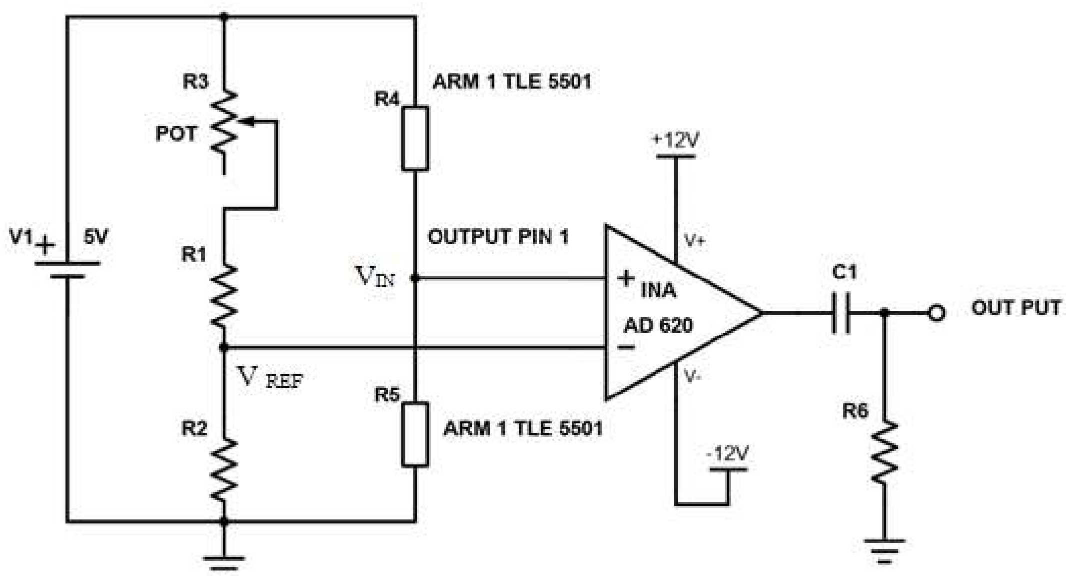


Fig 3.2. Receiver schematic diagram (Configuration I).

The TMR sensor output pin 1, V_{IN} is connected to an instrument amplifier whose second input is a reference voltage V_{REF}. The out voltage is coupled to a capacitor to filter out the DC part. The filtered output voltage is considered for target detection. An adjustable resistor R3 (POT) is connected with R_1 to adjust V_{REF} for zeroing of dc input.

Another variation (Configuration-II) of receiver circuit used is given in figure 3.3. Here the two inputs of the amplifier are taken from two arms of TMR IC. SIN _N and COS _P outputs (pin 7 & pin 1 of TLE5501) are connected to the input terminal of instrument amplifier through coupling capacitors C_2 and C_3.

(a) Resistors R5, R6 : 100 kΩ, 100 kΩ
(b) Capacitors C2, C3 : 10 µF, 10 µF
(c) Amplifier : AD 620
(d) Gain : 150
(e) TMR IC : TLE 5501, Placed radially at the centre of the coil (parallel).
(f) DC Supply : 5V

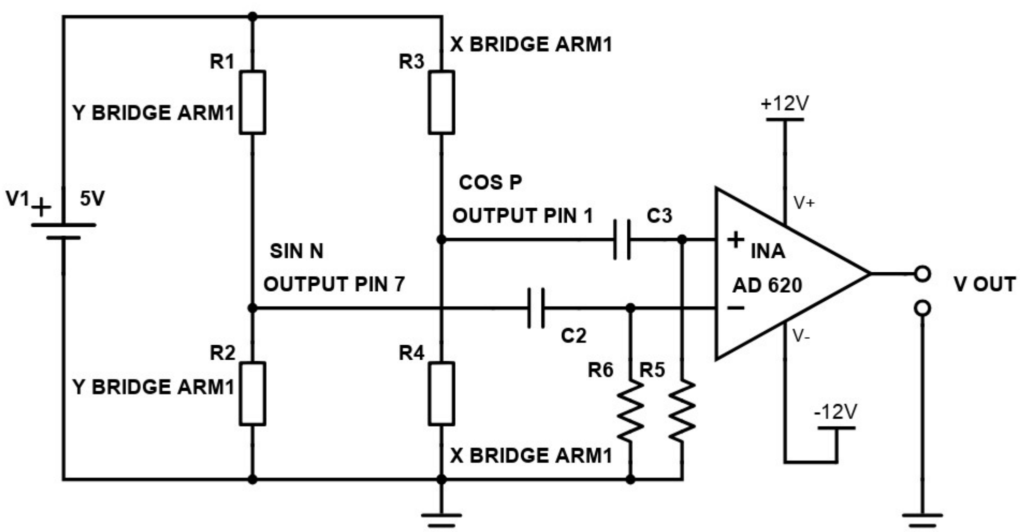


Fig 3.3. Receiver schematic diagram (Configuration-II).

3.1.SIGNAL PROCESSING AND ANALYSIS

The output of the sensor-amplifier circuit is captured by an NI ELVIS-II board and displayed using LabVIEW. The sensor output without any target in the vicinity of search coil is recorded and used as the reference. The sensor output varies with the proximity of a metal target. This alters the shape and magnitude of sensor output. The difference in sensor output is found out by comparing the present signal with the reference signal. Presence of a metal target produces an observable variation in signal from refence.

CHAPTER 4
RESULTS AND INFERENCES

The project is implemented in different stages. The results and inferences of each stages are described here. The search coil and receiver circuit are set up as explained in section 3.1 and 3.2. The coil is placed perpendicular to the ground. Experiments are conducted with target placed at certain distances at the axis of the coil. Air is the only medium used during the experiments.

4.1. EXPERIMENT 1

The transmitter as given in figure 3.1 is implemented for the experiment. The circuit parameters are as described in section 3.1. The receiver is implemented as in figure 3.2 (Configuration-I). The receiver circuit parameters are as described in section 3.2. The target used is an aluminium plate of diameter 20 cm and 1.5 mm thick.

The voltage impulse that appears across the coil L_1 is measured. It has a peak value of 25V and exponentially dies down in 2.5 ms. Figure 4.1 shows the voltage impulse across the search coil (V_{COIL}) with respect to the switch control voltage (V_{CTRL}).

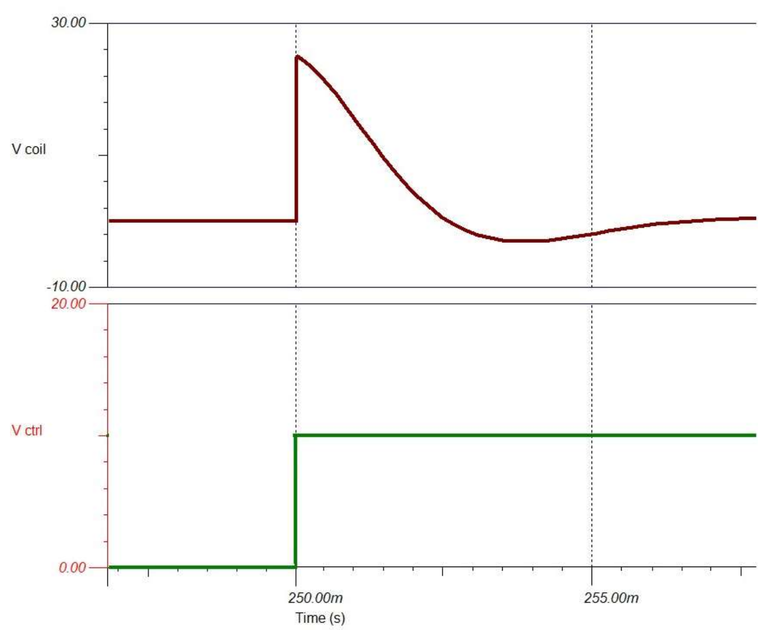


Fig 4.1. Voltage across coil L_1 (V_{COIL}) and switch control voltage (V_{CTRL}).

The electric impulse results in an impulse magnetic field. The sensor output is measured first without any metallic target, and then with metallic target at distance varying from 10 cm to 50 cm from the centre of the coil. The sensed signals are compared to that of reference (without metal target) for any variations with respect to target placement at certain distances from the centre of the coil.

The reference and target signal obtained from the sensor with the receiver configuration-I is shown in figure 4.2 below. The target A and B are at axial distances 10 cm (Target A) and 20 cm (Target B) respectively from the centre of the search coil. As the target distance increase from the centre of the coil, the target curve peak come closer to the reference curve peak. Maximum distance from which target could be detected is approximately 30 cm.

Inferences: The presence of a metal target resulted in variation of amplitude and time of occurrence of the peak of the signal. As the distance of the target from the coil decreased the peak amplitude increased and the peak occurred earlier. The maximum range of target detection is 30 cm.

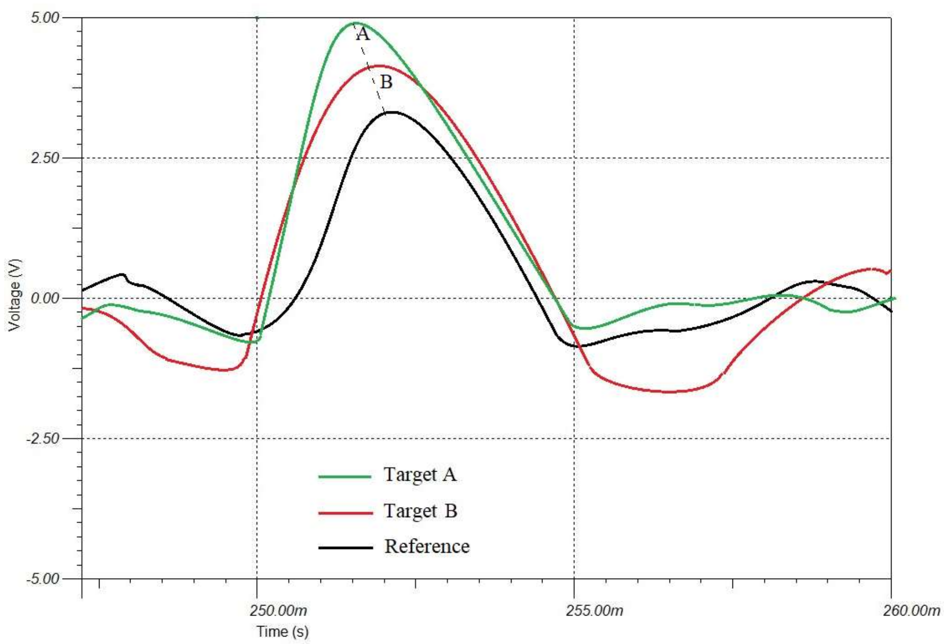


Fig 4.2. Reference and target signals from sensor. Target A is at 10 cm, Target B at 20 cm and reference without any target. TMR sensor in configuration-I with parallel sensor arrangement.

4.2. EXPERIMENT 2

The same transmitter design as in experiment 1 as given in figure 3.1 is implemented for the experiment 2. The receiver is implemented as in figure 3.3. The circuit parameters are as per Configuration-II mentioned in section 3.2.

The target used is an aluminium plate of diameter 20 cm and 1.5 mm thick, same as earlier experiment. Target is placed at distances 15 cm, 30 cm and 45 cm (Target A, B and C respectively). It is observed that the presence of a metallic target in the axis of the coil produces a visible difference at the peak of the curve. The peak amplitude as well as the time of occurrence of the peak varies with the target position. As the target comes nearer to the coil the peak amplitude increases and occurs earlier than the reference signal peak. Likewise, as the target moves away from the centre of the coil, the peak of the curve comes closer to the reference and the difference reduces. The maximum possible range of the target which produced a visible difference in the curves is approximately 52 cm.

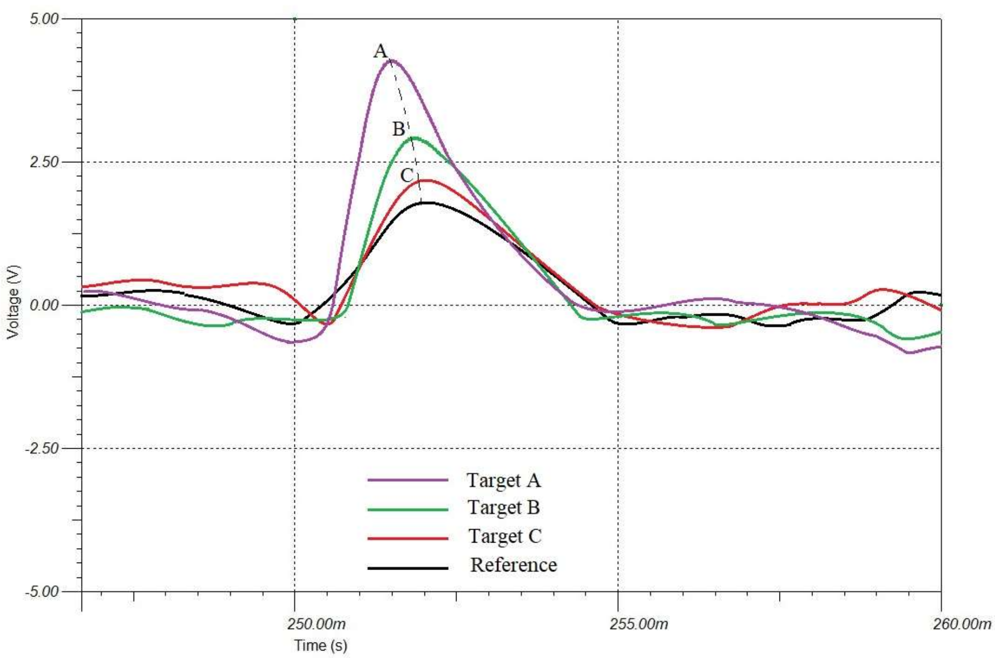


Fig 4.3. Reference and target signals from sensor. Target A, B and C are at 15, 30 and 45 cm from the centre of the coil and reference signal without any target. TMR sensor in Configuration-II with parallel sensor arrangement.

Inferences: The presence of a metal target resulted in variation of amplitude and time of occurrence of the peak of the signal. As the distance of the target from the coil decreased the peak amplitude increased and the peak occurred earlier. The maximum range of target detection is 52 cm. Configuration II is found better compared to configuration I as target detection range is high. This could be the result of cancellation of common mode signals from both the arms of the TMR sensor.

4.3. EXPERIMENT 3

The transmitter and receiver configurations remained same as in experiment 1. The alignment of the TMR IC is changed to, perpendicular to the plane of the coil. The reference curve and target curves are recorded. It is observed that the difference between target curves and reference curve is negligible at a distance more than 10 cm.

Inferences: The presence of a metal target resulted in negligible variation of amplitude and time of occurrence of the peak of the signal. Maximum range of detection is less than 10 cm.

4.4. EXPERIMENT 4

The transmitter and receiver configurations remained same as in experiment 2. The alignment of the TMR IC is changed to, perpendicular to the plane of the coil. The reference curve and target curves are recorded. It is observed that the difference between target curves and reference curve is negligible at a distance more than 15 cm.

Inferences: The presence of a metal target resulted in negligible variation of amplitude and time of occurrence of the peak of the signal. The maximum range of detection is less than 15 cm. The reduction in detection ranges observed in experiment 3 and 4 could be due to the high sensitivity of TMR sensor in plane horizontal to it. The experiment results are tabulated below in Table 4.1.

Table 4.1 summary of experiment results

Experiment Sl. No.	Configuration	Sensor Arrangement	Maximum range of detection (cm)
1	Configuration-I	Parallel	30
2	Configuration-II	Parallel	52
3	Configuration-I	Perpendicular	10
4	Configuration-II	perpendicular	15

CHAPTER 5

SUMMARY AND FUTURE WORK

Landmines can remain dangerous many years after a conflict has ended, harming people and the economy. Landmine detectors are instrumental in detecting and removing them. Modern technologies can be used effectively to improve the detection capabilities of mine detectors. Improving the positive detection probability and reducing false alarms is the key challenge in designing new detection devices. The high magnetic field sensitivity and characteristics of TMR sensors can aid in enhancing the performance of mine detectors.

The project work includes study of metal detector technologies currently available and GMR and TMR technology. The project work uses a coil as transmitter, to generate impulsive magnetic fields and a TMR sensor as the receiver. The magnetic field generated by the coil interacts with the metal target. The presence of a metallic target will alter the magnetic field which can be sensed by a TMR sensor. Due to the high sensitivity of TMR sensors even slight changes in the field can be picked up.

Experiments are conducted with various configurations of the sensor and coil. The sensor outputs are gathered using NI ELVIS II board and LabVIEW platforms. The signals are visually analysed for target information by comparing with a reference signal. It is observed that a target of 20 cm diameter at the range of 52 cm could be detected with 20 cm diameter coil with parallel arrangement of sensor IC with respect to the coil. Other configurations are also tried but found less effective compared to the former.

5.1. RECOMMENDATIONS FOR THE FUTURE WORK

The sensing range of the device need further improvement along with design of signal analysis and detection circuit. The future scope of the project is enumerated below.

1. The magnetic field intensity at the target plays an important role in range of detection. To improve the magnetic field intensity at the target, the shape, size and number of turns need to be optimized.
2. The sensor used is a TMR angle sensor. Better TMR ICs designed for low field detection with high SNR can be used to increase detection range further. Using a grid of multiple TMR sensors can further improve the characteristics of the detector.

3. Currently the target is detected using visual comparison of sensor outputs with a reference signal. This process can be implemented using a signal analysis circuit. The circuit will need to sample and store a reference signal and compare it with the sensor output continuously. The peaks of reference and target signal can be compared using a comparator. The output can be comprehended as a target if it meets certain pre-decided criteria.
4. The transmitter, receiver and signal analysing circuit need to be assembled in a single hand held module with adequate power supply. A user interface is also required for controlling the device and monitoring the output.

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