

สำนักหอสมุดกลาง พระจอมเกล้าลาดกระบัง

**EFFECTS OF PHASE-CONTROLLED MAGNETIZATION IN  
PERMANENT MAGNET PROPERTIES**



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|                       |                                                                                                   |
|-----------------------|---------------------------------------------------------------------------------------------------|
| <b>Thesis Title</b>   | Effects of Phase-Controlled Magnetization in Permanent Magnet Properties                          |
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## ABSTRACT

In this work, a new magnetizer consisting of a phase controlled converter and a magnetic fixture has been designed and constructed. Its magnetic fixture was described. The magnetizer performance showed a limited values of magnetizing field of 1.6 T, peak input ac voltage of 311.12 V, average load voltage of 172.10 V and average load current of 28.92 A. The magnetic fixture had an inductance of 0.521 H and resistance of 8.375  $\Omega$ . The results showed that the current decay time in capacitor discharge magnetizer took longer duration than the invented magnetizer which took only 3 ms. Neodymium magnet, a type of rare-earth magnet, is a permanent magnet made from an alloy of neodymium, iron and boron to form the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  tetragonal crystalline structure. Specimens of permanent magnets were made by hydraulic press pressed a neodymium powder in a die compaction. The effects of magnetization in permanent magnet properties were studied. Experimental results confirmed that the phase-controlled magnetizer had an advantage of higher remanence from specimens magnetized with additional inversion mode.

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# CHAPTER 1

## INTRODUCTION

This chapter introduces the background of powder metallurgy in magnets applications. After that, objectives, scopes and expected benefits of this work are given.

### 1.1 Significance and Background

Powder Metallurgy has an ability to produce complex structural parts with savings material and energy. P/M is used in the production of soft magnetic materials for direct current applications and for permanent magnets because P/M applications permit production to final shape with a minimum of subsequent machining and grinding. P/M permanent magnets was firstly developed in the early 1960's. The automobile has been the basis for most industrial applications of P/M. The development of permanent magnet materials has led to stronger magnets with higher coercivity. Neodymium magnet possesses the highest energy density. In manufacturing process of this magnetic type, after shaping of non-magnetic powders, the shaped parts need to be magnetized with an intense magnetic field. SCR-type magnetizer offers a potential of economic advantages compared to capacitor-type system due to minimal maintenance and low cost system.

This work a phase-controlled converter was invented for magnetizing P/M permanent magnets with an additional inversion mode and studied the magnetization effects in neodymium magnets properties. Design and construction for the phase-controlled magnetizer and the magnetic fixture were described. The magnetizer performance was investigated and improved. The results and discussions are presented.

### 1.2 Objectives

- 1.2.1 To design and invent a phase-controlled magnetizer
- 1.2.2 To study P/M process for permanent magnet applications
- 1.2.3 To study effects of magnetization in permanent magnet properties
- 1.2.4 To study hypothesis of measurement

### 1.3 Scopes

- 1.3.1 Phase controlled converter
- 1.3.2 Magnetization

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1.3.3 P/M process for bonded neodymium magnet

1.3.4 Permanent magnet properties

## **1.4 Expected Benefits**

1.4.1 Invent a phase-controlled magnetizer.

1.4.2 Improve a magnetizer performance.



## CHAPTER 2

### REVIEW OF LITERATURE

This chapter presents the basis to design phase-controlled magnetizer, which consists of magnetic fixture, dc power supply, permanent magnet applications. In addition, literature reviews are included to identify merits and challenges of this work. First, the system topology and parameters are described. Then the material properties, electricity and magnetism are followed.

#### 2.1 Magnetizer

There are four types of systems used to magnetize permanent magnetic materials. The first is a permanent magnet used to magnetize other magnetic materials of lower  $H_c$  value. The second is a direct current magnetizer. Third is a half cycle magnetizer and the fourth type magnetizer is a capacitor discharge, which is the most common because it is the most versatile [1].

However, to classify magnetizers by their structures there will be three types of magnetizer. The first is a permanent magnet used to magnetize other magnetic materials of lower  $H_c$  values. The second is capacitor-discharge impulse magnetizer. The third is SCR-type magnetizer. In the second and the third, a dc current is conducted through the magnetic fixture similarly but their energy supplies are different.

##### 2.1.1 Permanent Magnet Magnetizer

A permanent magnet is used to magnetize other magnetic materials. The magnetized materials requiring a permanent magnet magnetizer always have a higher remanence.

##### 2.1.2 Capacitor-type Magnetizer

The capacitor-discharge magnetizers are available with several voltage and energy levels. The typical voltage levels are 400 volts and 900 volts for computer grade capacitors, 2000 volts and 3000 volts for oil filled capacitors. Energy levels depend on the capacitor values and voltage chosen. Capacitors chosen are ranging from 100 microfarads to hundreds of thousands of microfarads [2].

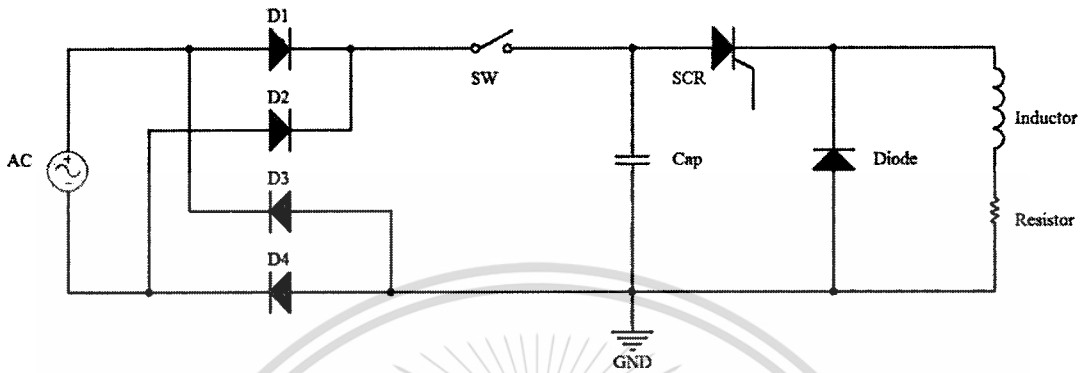
The main operating procedure of the capacitor-type system shown in **Figure 2.1** is given below: The rectified power supply provides the initial charge for capacitor. Initially, the capacitor is charged with polarity. In order to transfer the energy from capacitor to the R-L load, the SCR

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must be turned-on. When the voltage in capacitor begins to reverse, the recovery diode  $D_R$  conducts. Therefore, the recovery diode prevents the capacitor voltage from being drop below 0 V. The capacitor C is recharged through a switch to its original voltage and polarity [3].



**Figure 2.1** Capacitor-discharge magnetizer.

Several researches have been conducted with this type of magnetizer [2-8]. There were three kinds of research; (1) field and waveform, (2) field simulation using finite-element analysis (FEA) and (3) circuit simulation using numerical analysis.

The advantage of a capacitor-discharge magnetizer is that the stored energy in the capacitor bank can be released in a short time period. It results in creating a very large-amplitude current pulse. These currents can generate very large magnetic field in the many cases where the physical size or configuration of the part limits the number of turns in the magnetizing fixture [2].

However, disadvantages of this type of magnetizer are a direct result of designing for high amplitude current. The cycle times of this type of magnetizer are slowed because of the storing of the energy on the capacitors requires several seconds. They are more expensive because of the high cost of the capacitors used to store the energy and then completely release it time after time. Service or replacement of the electrolytic capacitors subjected to this type of service becomes a necessity after a period of time [2].

### 2.1.3 SCR-type Magnetizer

The SCR-type magnetizer is a very simple magnetizing system limited in the amount of field generated because it is restricted to the power available which dependent on the ac line current capacity. The main operating procedure of SCR-type system of **Figure 2.2** is as follows: This system is similar to ac voltage rectifier [3]. The SCR delivers the positive half-wave pulse.

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The rectifier circuits are uncontrollable; that is, their output voltage is a function of system parameters and cannot be adjusted in response to parametric changes, such as variations in load ( $I_d$ ) or ac voltage ( $V_s$ ). However, rectifier circuit can be controlled if replace the diodes with SCRs (Silicon Controlled Rectifiers). This device is one member of a family of controllable switches known collectively as thyristors. The SCR will not conduct when forward biased until an appropriate control signal is applied to a third terminal, called the gate [9].

A rectifier circuit containing one or more SCR devices for controlling the output voltage is known as a phase-controlled rectifier. In addition to providing voltage control, phase-controlled rectifiers can be designed to permit power to flow from the dc side to ac side (as long as there is a

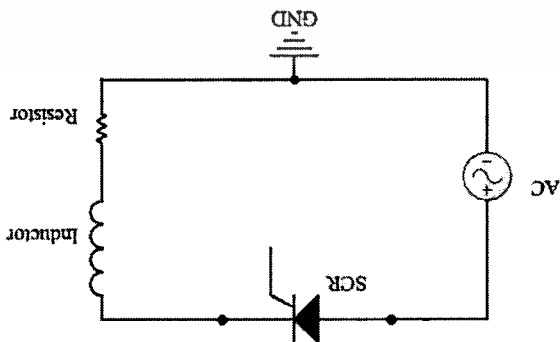
As mention, several researches have been conducted with capacitor-type magnetizer but there is not a single information on SCR-type. This work aims to invent a phase-controlled magnetizer which is a complementary of SCR-type magnetizer. The design of phase-controlled magnetizer is based on phase controlled converter principle as explained below.

## 2.2 Phase Controlled Converter

Kim, P. S. [3] reported that the SCR-type magnetizer system offered potential economic advantages compared to capacitor-type system and another benefit of this system is its relative weight significantly reduced in relation to a capacitor-type. And also concluded that SCR-type magnetizer system appears to be particularly attractive from an economic point of view.

Advantages of SCR-type magnetizer are it is a simple system with minimal maintenance, typically the least costly system and its ability to generate pulse fields at very fast cycle rates [1].

Figure 2.2 SCR-type magnetizer (the concept of this work).



SCR discussed in Section 2.2.

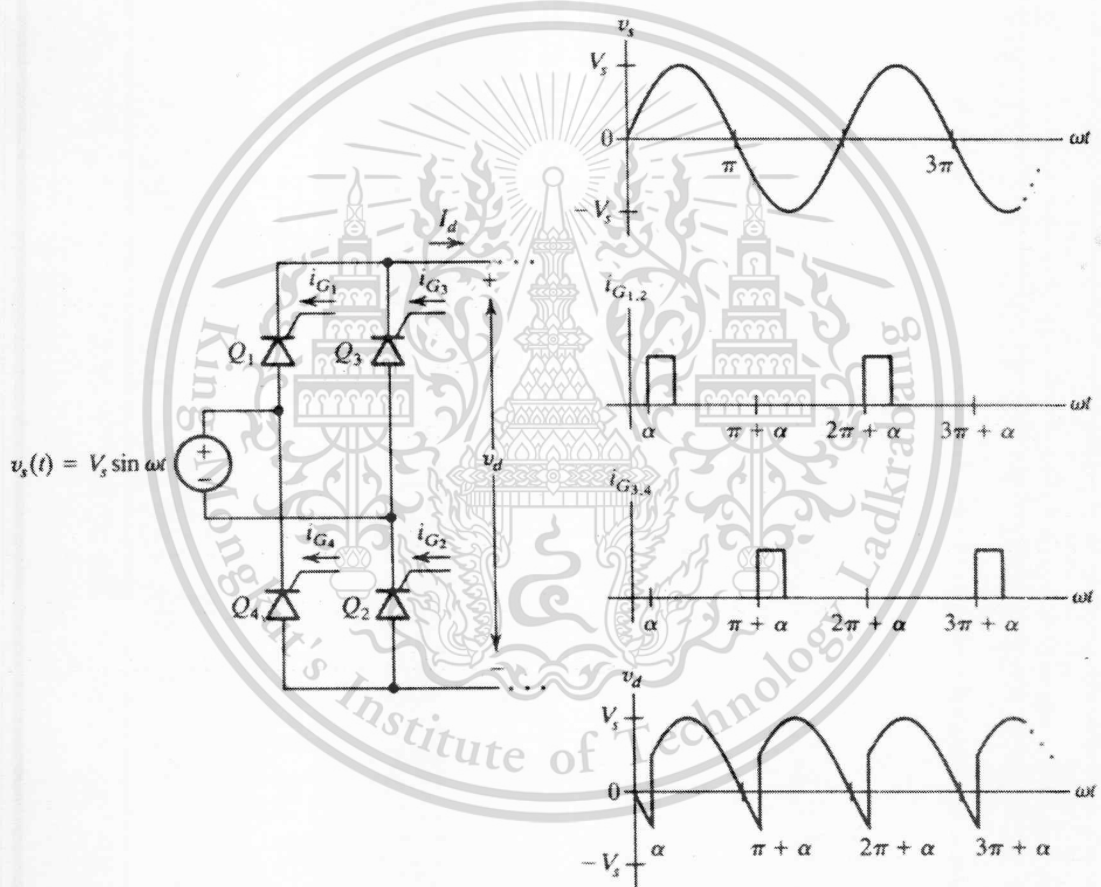
The energy densities of this type magnetizer system are proportional to the trigger position of

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source of energy on the dc side). This process is called inversion, and a circuit operating in this way is called a phase-controlled inverter [9].

### 2.2.1 Single-phase Full-wave Converter

A full-wave phase-controlled bridge rectifier consists of two diagonal pair of thyristors conduct for some part of each half-cycle. The behavior of the output voltage waveform  $v_d$  is referring to the diode bridge rectifier, one pair of diode is turned off by the action of the second pair turning on. In phase-controlled rectifier, if the second pair does not turn on, the load current must continue to flow in the first pair, keeping it on [9].



**Figure 2.3** Phase-controlled bridge rectifier with no ac-side (commutating) reactance [9].

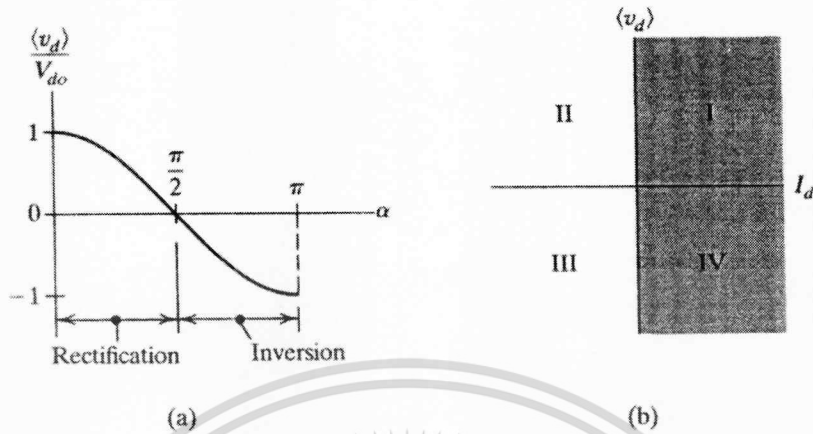
The average value of  $v_d$ , calculated from the waveform of  $v_d$  in **Figure 2.3** is

$$v_d = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s \sin \omega t d(\omega t) = \frac{2V_s}{\pi} \cos \alpha \quad (2.1)$$

Where  $\alpha$  is a firing angle in the unit of degree (one cycle of ac has 360°). The voltage as a function of  $\alpha$  is plotted in **Figure 2.4**. The most interested characteristic of the relationship is



that, for  $\pi/2 < \alpha < \pi$ , the average value of the output voltage is negative. Therefore, over this range of  $\alpha$ , power is flowing from dc side to the ac side, called inversion.



**Figure 2.4** (a) Control characteristic and (b) quadrants of operation for the bridge rectifier of

**Figure 2.3 [9].**

### 2.2.2 Operation Mode

The phase-controlled rectifier is operated to conduct a power from ac side to dc side, called rectification mode. When conducting a power from dc side to ac side, called inversion mode. The designed magnetizer is a combination of these two processes.

#### 2.2.2.1 Rectification Mode

The rectification mode is operating in the rectification region of the phase-controlled rectifier, where the firing angle is in a range of  $0 < \alpha < \pi/2$ . In this operating region the system conducts the power from ac to dc. The phase-controlled magnetizer uses this mode for a steady-state magnetizing field to magnetize permanent magnets.

#### 2.2.2.2 Inversion Mode

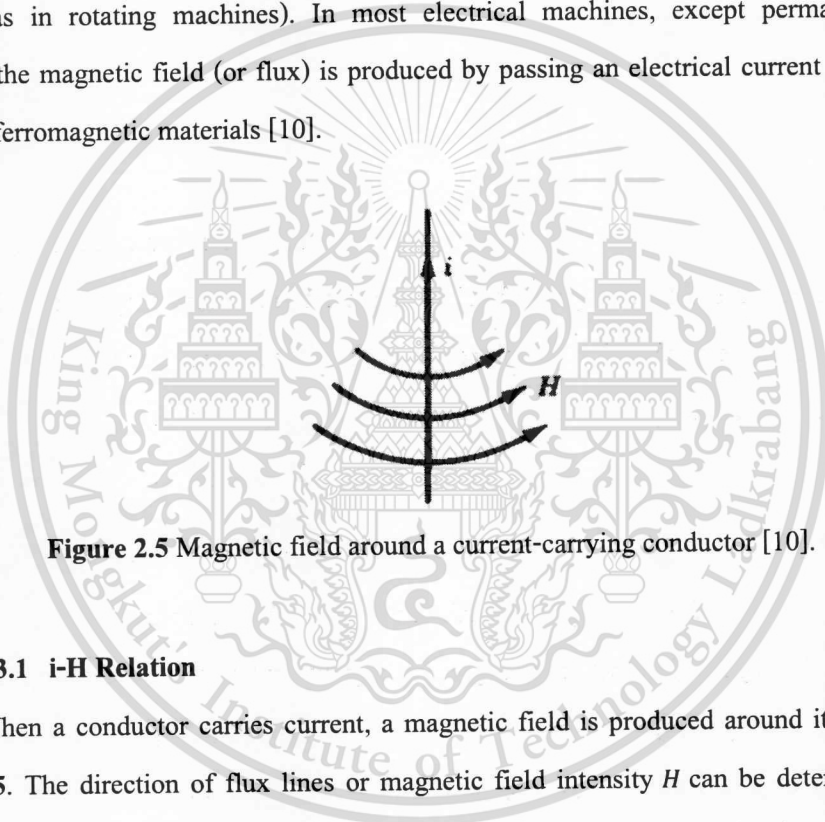
The inversion mode is operating in the inversion region, where the firing angle is in a range of  $\pi/2 < \alpha < \pi$ . In this operating region, the system conducts power from dc side to ac side. The phase-controlled magnetizer uses this mode to decay the current to zero. It is the fastest way to decay the current by operating the converter at the value of  $\alpha$  that produces the maximum negative voltage. The additional inversion mode was expected to give an advantage of remanence in permanent magnet materials after being magnetized.

### 2.2.3 Commutation Failure

It is necessary to ensure that the commutation is completed before the next zero-crossing of line voltage when a phase-controlled rectifier is operating in the inversion region. If commutation were not complete by this time, the current in the SCR pair that is turning off would begin to increase, thus keeping the pair on.

## 2.3 Magnetic Circuit

In electrical machines, the magnetic circuits may be performed by ferromagnetic materials only (as in transformers) or by ferromagnetic materials in conjunction with an air medium (as in rotating machines). In most electrical machines, except permanent magnet machines, the magnetic field (or flux) is produced by passing an electrical current through coils wound on ferromagnetic materials [10].



**Figure 2.5** Magnetic field around a current-carrying conductor [10].

### 2.3.1 i-H Relation

When a conductor carries current, a magnetic field is produced around it, as shown in **Figure 2.5**. The direction of flux lines or magnetic field intensity  $H$  can be determined by the *thumb rule*, which states that if the conductor is held with the right hand with the thumb indicating the direction of current in the conductor, then the fingertips will indicate the direction of magnetic field intensity [10].

The relationship between current and field intensity can be obtained by using *ampere's circuit law*, which states that the line integral of the magnetic field intensity  $H$  around a closed path is equal to the total current linked by the contour.

$$\oint \mathbf{H} \cdot d\mathbf{l} = \sum i \quad (2.2)$$



Where  $H$  is the magnetic field intensity at a point on the contour and  $dl$  is the incremental length at that point. If  $\theta$  is the angle between vectors  $\mathbf{H}$  and  $d\mathbf{l}$ , then

$$\oint H \, dl \cos \theta = \sum i \tag{2.3}$$

### 2.3.2 B-H Relation

The magnetic field intensity  $H$  produces a magnetic flux density  $B$  everywhere it exists. These quantities are functionally related by

$$B = \mu H \tag{2.4}$$

$$B = \mu_r \mu_0 H \tag{2.5}$$

Where  $\mu$  is a characteristic of the medium and is called the permeability of the medium,  $\mu_0$  is the permeability of free space and is defined value of  $4\pi \times 10^{-7} \text{H/m}$ ,  $\mu_r$  is the relative permeability of the medium,  $H$  is measured in amperes per meter (At/m),  $B$  is measured in webers per square meter ( $\text{Wb/m}^2$ ) or in the International System of Units, tesla (T). An older that is often used for magnetic flux density is the gauss (G), where 1 T or  $1 \text{ Wb/m}^2$  is the same as 10000 G.

For free space or electrical conductors (such as aluminium or copper) or insulators, the value of  $\mu_r$  is unity. However, for ferromagnetic materials such as iron, cobalt, nickel, the value of  $\mu_r$  varies from several hundred to several thousand. For materials used in electrical machines,  $\mu_r$  varies in the range of 2000 to 6000. A large value of  $\mu_r$  implies that a small current can produce a large flux density in the machine [10]. The relative permeability for various materials are listed in Table 2.1.

**Table 2.1** The relative permeability of materials [11].

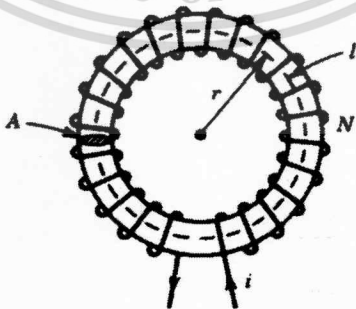
| Material  | $\mu_r$    |
|-----------|------------|
| Bismuth   | 0.9999986  |
| Paraffin  | 0.99999942 |
| Wood      | 0.9999995  |
| Silver    | 0.99999981 |
| Aluminum  | 1.00000065 |
| Beryllium | 1.00000079 |

**Table 2.1** The relative permeability of materials [11] (Cont.).

| Material          | $\mu_r$ |
|-------------------|---------|
| Nickel chloride   | 1.00004 |
| Manganese sulfate | 1.0001  |
| Nickel            | 50      |
| Cast iron         | 60      |
| Cobalt            | 60      |
| Powdered iron     | 100     |
| Machine steel     | 300     |
| Ferrite (typical) | 1000    |
| Permalloy 45      | 2500    |
| Transformer iron  | 3000    |
| Silicon iron      | 3500    |
| Iron (pure)       | 4000    |
| Mumetal           | 20000   |
| Sendust           | 30000   |
| Supermalloy       | 100000  |

**2.3.3 Magnetic Equivalent Circuit**

When current  $i$  flows through the coil of  $N$  turns, magnetic flux is mostly confined in the core material. The flux outside the core, called *leakage flux*.



**Figure 2.6** Toroid magnetic circuit [10].

Consider a path at a radius  $r$ . The magnetic intensity on this path is  $H$  and, from *ampere’s circuit law*,

$$\oint \mathbf{H} \cdot d\mathbf{l} = Ni \quad (2.6)$$

$$Hl = Ni \quad (2.6a)$$

The quantity  $Ni$  is called the *magnetomotive force (mmf)  $F$* , and its unit is ampere-turn.

$$H = \frac{N}{l} i \quad (2.7)$$

From **Equations 2.4 and 2.7**

$$B = \frac{\mu Ni}{l} \quad (2.8)$$

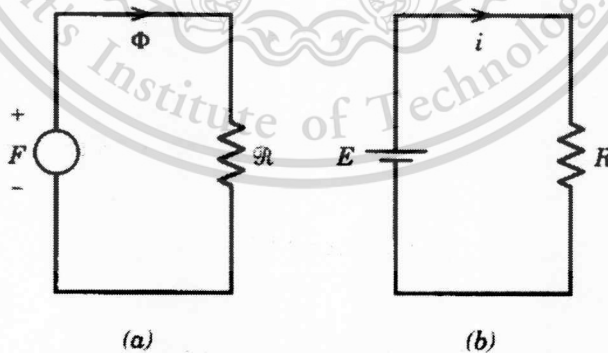
The flux crossing the cross section is

$$\Phi = BA \quad (2.9)$$

Where  $B$  is the average flux density in the core and  $A$  is the area of cross section of the core. The average flux density may correspond to the path at the mean core length. If  $H$  is the magnetic intensity for this path, then from **Equations 2.8 and 2.9**

$$\Phi = \frac{\mu Ni}{l} A = \frac{Ni}{l/\mu A} \quad (2.10)$$

$$\Phi = \frac{Ni}{\mathfrak{R}} \quad (2.11)$$



**Figure 2.7** Analogy between (a) magnetic circuit and (b) electric circuit [10].

$$\Phi = \frac{F}{\mathfrak{R}} \quad (2.12)$$

Where

$$\mathfrak{R} = \frac{l}{\mu A} = \frac{1}{P} \quad (2.13)$$

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$\mathfrak{R}$  is called the *reluctance* of the magnetic path and  $P$  is called the *permeance* of the magnetic path. **Equations 2.11** and **2.12** suggest that the driving force in the magnetic circuit of **Figure 2.6** is the magnetomotive force  $F$ , which produces a flux  $\Phi$  against a magnetic reluctance  $\mathfrak{R}$ . The magnetic circuit can therefore be represented by a magnetic equivalent circuit as shown in **Figure 2.7a**. Also note that **Equation 2.12** has the form of *ohm's law* for an electric circuit. The analogous electrical circuit is shown in **Figure 2.7b**. A magnetic circuit is often looked upon as analogous to an electric circuit. The analogy is illustrated in **Table 2.2**.

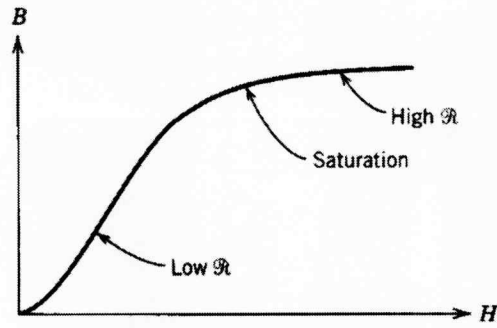
**Table 2.2** Electrical versus magnetic circuits [10].

|               | Electric Circuit                             | Magnetic Circuit                                     |
|---------------|----------------------------------------------|------------------------------------------------------|
| Driving force | Emf ( $E$ )                                  | Mmf ( $F$ )                                          |
| Produces      | Current ( $i = E/R$ )                        | Flux ( $\Phi = F/\mathfrak{R}$ )                     |
| Limited by    | Resistance ( $R = l/\sigma A$ ) <sup>a</sup> | Reluctance ( $\mathfrak{R} = l/\mu A$ ) <sup>a</sup> |

<sup>a</sup>  $\sigma$ , Conductivity;  $\mu$ , permeability.

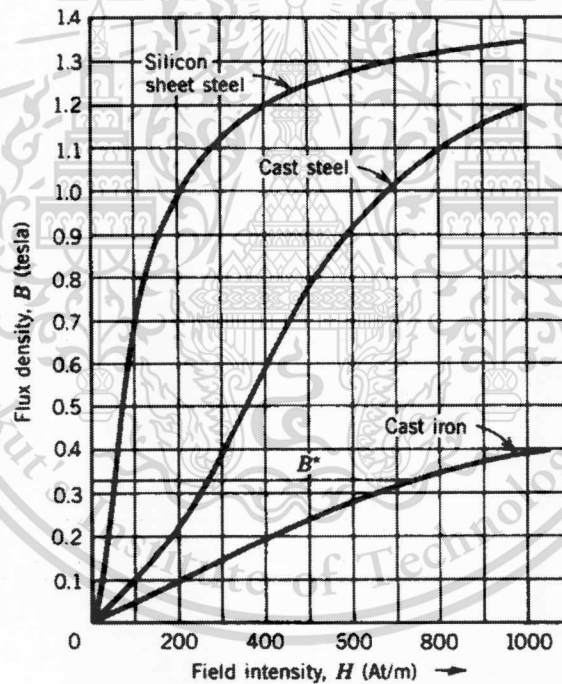
**2.3.4 Magnetization Curve**

If the magnetic intensity in the core is increased by increasing current, the flux density in the core changes in the way shown in **Figure 2.8**. The flux density  $B$  increases almost linearly in the region of low values of the magnetic intensity  $H$ . However, at higher values of  $H$ , the change of  $B$  is nonlinear. The magnetic material shows the effect of saturation. The  $B$ - $H$  curve, shown in **Figure 2.8**, is called the *magnetization curve*. The reluctance of the magnetic path is dependent on the flux density. It is low when  $B$  is low, high when  $B$  is high. The magnetic circuit differs from the electric circuit in this respect; resistance is normally independent of current in an electric circuit, whereas reluctance depends on the flux density in the magnetic circuit [10].



**Figure 2.8**  $B$ - $H$  characteristic [10].

The  $B$ - $H$  characteristic of magnetic core, is shown in **Figure 2.9**. Note that to establish a certain level of flux density  $B$  in the various magnetic materials the values of current required are different.



**Figure 2.9** Magnetization curves [10].

### 2.3.5 Magnetic Circuit with Air Gap

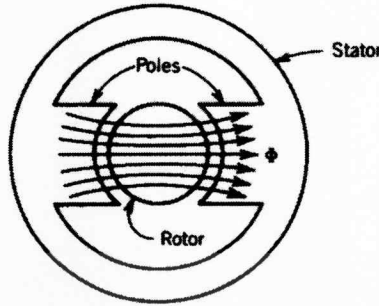
In electric machines, the rotor is physically isolated from the stator by the air gap. A cross-sectional view of a dc machine is shown in **Figure 2.10**. Practically the same flux is present in the poles (made of magnetic core) and the air gap. To maintain the same flux density, the air gap will require much more mmf than the core. If the flux density is high, the core portion of the

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magnetic circuit may exhibit a saturation effect. However, the air gap remains unsaturated, since the  $B$ - $H$  curve for the air medium is linear ( $\mu$  is constant) [10].



**Figure 2.10** Cross section of a rotating machine [10].

The magnetic circuit, having two or more media, such as the magnetic core and air gap in **Figure 2.10**, is known as a composite structure. For the purpose of analysis, a magnetic equivalent circuit can be derived from the composite structure.

**Figure 2.11a.** The driving force in this magnetic circuit is the mmf,  $F = Ni$ , and the core medium and the air gap medium can be represented by their corresponding reluctances. The equivalent magnetic circuit is shown in **Figure 2.11b**.

$$\mathcal{R}_c = \frac{l_c}{\mu_c A_c} \quad (2.14)$$

$$\mathcal{R}_g = \frac{l_g}{\mu_0 A_g} \quad (2.15)$$

$$\Phi = \frac{Ni}{\mathcal{R}_c + \mathcal{R}_g} \quad (2.16)$$

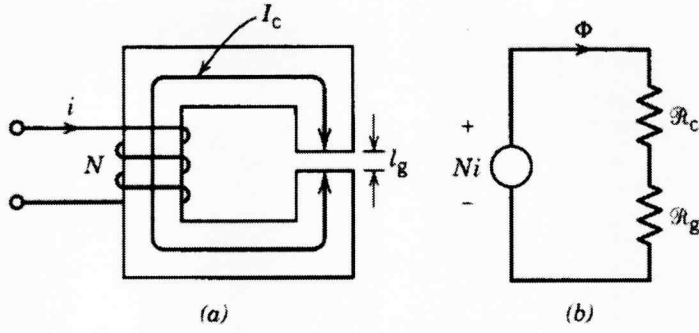
$$Ni = H_c l_c + H_g l_g \quad (2.17)$$

Where  $l_c$  is the mean length of the core and  $l_g$  is the length of the air gap.

The flux densities are

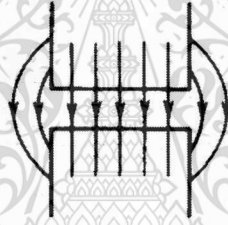
$$B_c = \frac{\Phi_c}{A_c} \quad (2.18)$$

$$B_g = \frac{\Phi_g}{A_g} \quad (2.19)$$



**Figure 2.11** Composite structure. (a) Magnetic core with air gap. (b) Magnetic equivalent circuit [10].

The fringing flux is shown in **Figure 2.12**. The effect of the fringing is to increase the cross-sectional area of the air gap. For small air gaps the fringing effect can be neglected. If the fringing effect is neglected, the cross-sectional areas of the core and the air gap are the same [10].



**Figure 2.12** Fringing flux [10].

### 2.3.6 Inductance

A coil wound on a magnetic core shown in **Figure 2.13a**, is frequently used in electric circuits. This coil may be represented by an ideal circuit element, called *inductance*, which is defined as the flux linkage of the coil per ampere of its current.

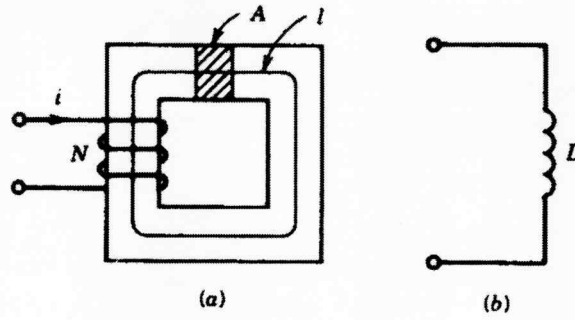
$$\lambda = N\Phi \quad (2.20)$$

$$L = \frac{\lambda}{i} \quad (2.21)$$

From **Equations 2.20, 2.21, 2.9, 2.4, and 2.13**,

$$L = \frac{N\Phi}{i} = \frac{N^2}{l/\mu A} \quad (2.22)$$

$$= \frac{N^2}{\mathfrak{R}} \quad (2.23)$$



**Figure 2.13** Inductance of a coil-core assembly. (a) Coil-core assembly. (b) Equivalent inductance [10].

**Equation 2.22** defines inductance in terms of physical dimensions, such as cross-sectional area and length of core, while **Equation 2.23** defines inductance in terms of the reluctance of the magnetic path. Note that inductance varies as the square of the number of turns.

## 2.4 Magnetic Materials

The externally applied magnetic field, sometimes called the *magnetic field strength*, is designated by  $H$  as in **Equation 2.7**. The magnetic induction, or magnetic flux density, denoted by  $B$ , represents the magnitude of the internal field strength within a substance that is subjected to an  $H$  field. Both  $B$  and  $H$  are field vectors, being characterized not only by magnitude, but also by direction in space [12].

Another field quantity,  $M$ , called the magnetization of the solid, is defined by the expression

$$B = \mu_0 H + \mu_0 M \quad (2.24)$$

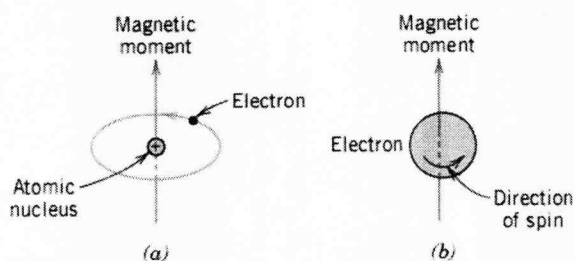
In the presence of an  $H$  field, the magnetic moments within a material tend to become aligned with the field and to reinforce it by virtue of their magnetic fields; the term  $\mu_0 M$  in **Equation 2.24** is a measure of this contribution.

### 2.4.1 Magnetism

The macroscopic magnetic properties of materials are a consequence of magnetic moments associated with individual electrons. Some of these concepts are relatively complex and involve some quantum-mechanical principles. Each electron in an atom has magnetic moments that originate from two sources. One is related to its orbital motion around the nucleus; being a moving charge, an electron may be considered to be a small current loop, generating a very small



magnetic field, and having a magnetic moment along its axis of rotation, as schematically illustrated in **Figure 2.14a** [12].



**Figure 2.14** Demonstration of the magnetic moment associated with (a) an orbiting electron and (b) a spinning electron [12].

Each electron may also be thought of as spinning around an axis and the magnetic moment is originated from this electron spin, which is directed along the spin axis as shown in **Figure 2.14b**. The spin magnetic moments can be in an “up” direction or in an antiparallel “down” direction [12].

The most fundamental magnetic moment is the Bohr magneton  $\mu_B$ , which is of magnitude  $9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2$ . For each electron in an atom the spin magnetic moment is  $\pm \mu_B$  (plus for spin up, minus for spin down). Furthermore, the orbital magnetic moment contribution is equal to  $m_l \mu_B$ ,  $m_l$  being the magnetic quantum number of the electron.

In each individual atom, orbital moments of some electron pairs cancel each other; this also holds for the spin moments. For example, the spin moment of an electron with spin up will cancel that of one with spin down. The net magnetic moment, then, for an atom is just the sum of the magnetic moments of each of the constituent electrons, including both orbital and spin contributions, and taking into account moment cancellation. The types of magnetism include diamagnetism, paramagnetism, and ferromagnetism; in addition, antiferromagnetism and ferrimagnetism are considered to be subclasses of ferromagnetism. All materials exhibit at least one of these types, and the behaviour depends on the response of electron and atomic magnetic dipoles to the application of an externally applied magnetic field [12].

#### 2.4.1.1 Diamagnetism

Diamagnetism is a very weak form of magnetism that is nonpermanent and persists only while an external field is being applied. It is induced by a change in the orbital motion of electrons due to an applied magnetic field. The magnitude of the induced magnetic moment is

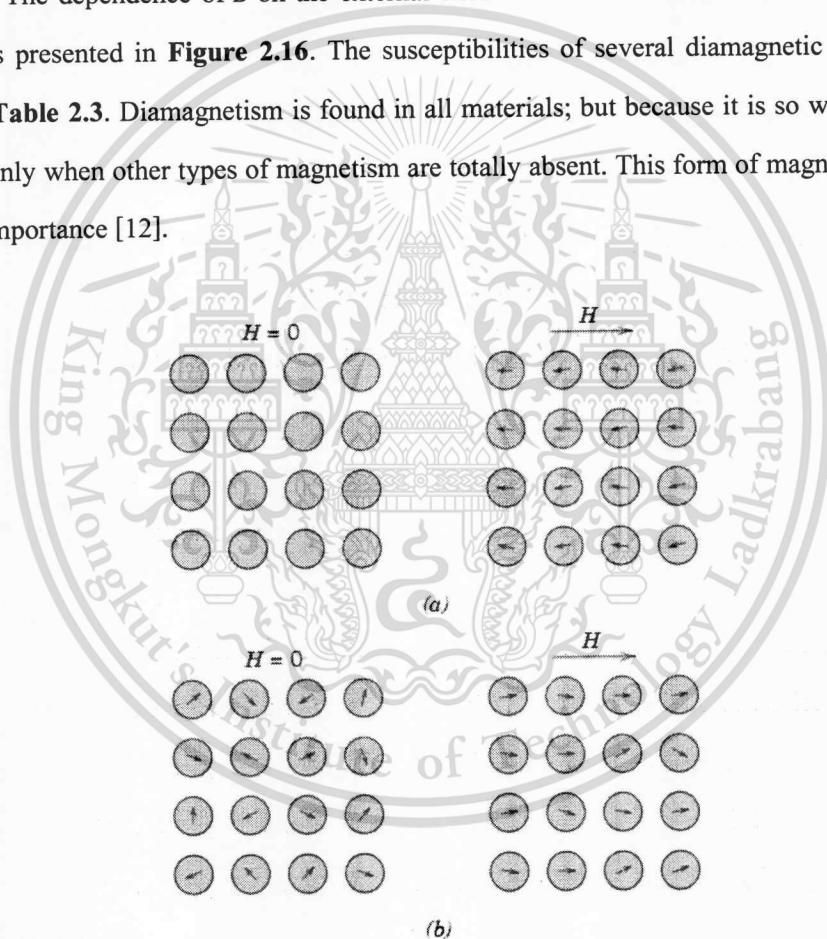
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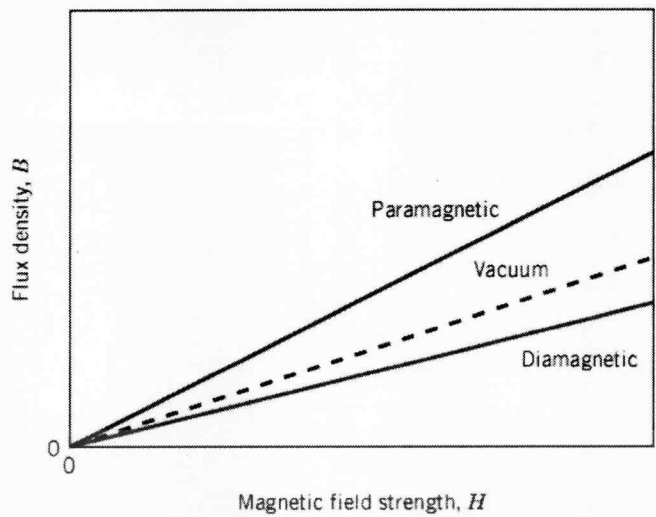


extremely small, and in a direction opposite to that of the applied field. Thus, the relative permeability  $\mu_r$  is less than unity (however, only very slightly), and the magnetic susceptibility is negative; that is, the magnitude of the  $B$  field within a diamagnetic solid is less than that in a vacuum. The volume susceptibility  $\chi_m$  for diamagnetic solid materials is on the order of  $-10^{-5}$ . When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak [12].

The atomic magnetic dipole configurations for a diamagnetic material with and without an external field is illustrated in **Figure 2.15a** (here, the arrows represent atomic dipole moments). The dependence of  $B$  on the external field  $H$  for a material that exhibits diamagnetic behavior is presented in **Figure 2.16**. The susceptibilities of several diamagnetic materials are shown in **Table 2.3**. Diamagnetism is found in all materials; but because it is so weak, it can be observed only when other types of magnetism are totally absent. This form of magnetism is of no practical importance [12].



**Figure 2.15** (a) The atomic dipole configuration for a diamagnetic material with and without a magnetic field. In the absence of an external field, no dipoles exist; in the presence of a field, dipoles are induced that are aligned opposite to the field direction. (b) Atomic dipoles configuration with and without an external magnetic field for a paramagnetic material [12].



**Figure 2.16** Schematic representation of the flux density  $B$  versus the magnetic field strength  $H$  for diamagnetic and paramagnetic materials [12].

**Table 2.3** Room-temperature magnetic susceptibilities for diamagnetic and paramagnetic materials [12].

| Diamagnetics    |                                                | Paramagnetics     |                                                |
|-----------------|------------------------------------------------|-------------------|------------------------------------------------|
| Material        | Susceptibility<br>$\chi_m$ (volume) (SI units) | Material          | Susceptibility<br>$\chi_m$ (volume) (SI units) |
| Aluminum oxide  | $-1.81 \times 10^{-5}$                         | Aluminum          | $2.07 \times 10^{-5}$                          |
| Copper          | $-0.96 \times 10^{-5}$                         | Chromium          | $3.13 \times 10^{-4}$                          |
| Gold            | $-3.44 \times 10^{-5}$                         | Chromium chloride | $1.51 \times 10^{-3}$                          |
| Mercury         | $-2.85 \times 10^{-5}$                         | Manganese sulfate | $3.70 \times 10^{-3}$                          |
| Silicon         | $-0.41 \times 10^{-5}$                         | Molybdenum        | $1.19 \times 10^{-4}$                          |
| Silver          | $-2.38 \times 10^{-5}$                         | Sodium            | $8.48 \times 10^{-6}$                          |
| Sodium chloride | $-1.41 \times 10^{-5}$                         | Titanium          | $1.81 \times 10^{-4}$                          |
| Zinc            | $-1.56 \times 10^{-5}$                         | Zirconium         | $1.09 \times 10^{-4}$                          |

2.4.1.2 Paramagnetism

For some solid materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments. In the absence of an external magnetic field, the orientations of these atomic magnetic moments are random, such that a piece of material possesses no net macroscopic magnetization. These atomic dipoles are free to rotate, and paramagnetism results when they preferentially align, by rotation, with an external



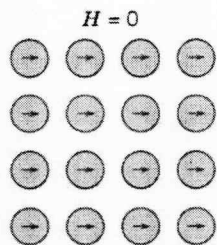
field as shown in **Figure 2.15b**. These magnetic dipoles are acted on individually with no mutual interaction between adjacent dipoles. The dipoles that align with the external field was enhanced by the applied magnetic field (giving rise to a relative permeability  $\mu_r$  that is greater than unity, and to a relatively small but positive magnetic susceptibility). Susceptibilities for paramagnetic materials range from about  $10^{-5}$  to  $10^{-2}$  (**Table 2.3**). A schematic  $B$ -versus- $H$  curve for a paramagnetic material is also shown in **Figure 2.16** [12].

Both diamagnetic and paramagnetic materials are considered to be nonmagnetic because they exhibit magnetization only when in the presence of an external field. Also, for both, the flux density  $B$  within them is almost the same as it would be in a vacuum [12].

2.4.1.3 Ferromagnetism

Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations. These are the characteristics of ferromagnetism, and they are displayed by the transition metals iron (as BCC  $\alpha$  ferrite), cobalt, nickel, and some of the rare earth metals such as gadolinium (Gd). Magnetic susceptibilities as high as  $10^6$  are possible for ferromagnetic materials [12].

Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to electron spin—uncancelled electron spins as a consequence of the electron structure. There is also an orbital magnetic moment contribution that is small in comparison to the spin moment. Furthermore, in a ferromagnetic material, coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field. This is schematically illustrated in **Figure 2.17**. The origin of these coupling forces is not completely understood, but it is thought to arise from the electronic structure of the metal. This mutual spin alignment exists over relatively large volume regions of the crystal called domains [12].

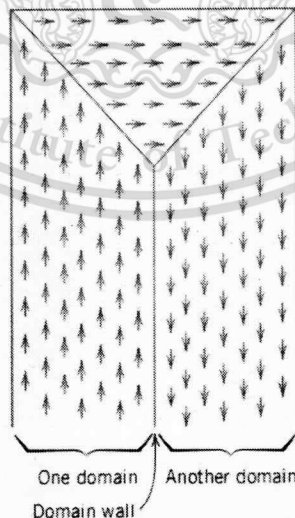


**Figure 2.17** Schematic illustration of the mutual alignment of atomic dipoles for a ferromagnetic material, which will exist even in the absence of an external magnetic field [12].

The maximum possible magnetization, or saturation magnetization  $M_s$ , of a ferromagnetic material represents the magnetization that results when all the magnetic dipoles in a solid piece are mutually aligned with the external field. The saturation magnetization is equal to the product of the net magnetic moment for each atom and the number of atoms present. For each of iron, cobalt, and nickel, the net magnetic moments per atom are 2.22, 1.72, and 0.60 Bohr magnetons, respectively [12].

### 2.4.2 Domains and Hysteresis

Any ferromagnetic, below the temperature of  $T_c$ , is composed of small-volume regions in which there is a mutual alignment in the same direction of all magnetic dipole moments, as illustrated in **Figure 2.18**. Such a region is called a domain, and each one is magnetized to its saturation magnetization. Adjacent domains are separated by domain boundaries or walls, across which the direction of magnetization gradually changes (**Figure 2.19**). Normally, domains are microscopic in size, and for a polycrystalline specimen, each grain may consist of more than a single domain. Thus, in a macroscopic piece of material, there will be a large number of domains, and all may have different magnetization orientations. The magnitude of the  $M$  field for the entire solid is the vector sum of the magnetizations of all the domains, each domain contribution being weighted by its volume fraction. For an unmagnetized specimen, the appropriately weighted vector sum of the magnetizations of all the domains is zero [12].

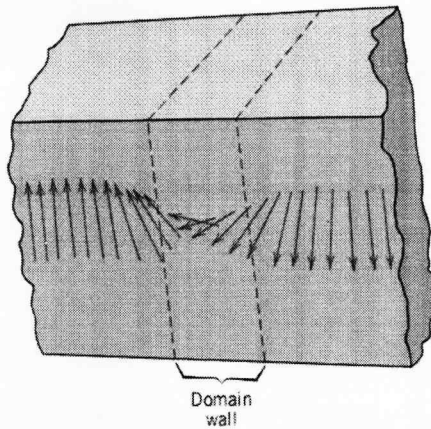


**Figure 2.18** Schematic depiction of domains in a ferromagnetic or ferromagnetic material; arrows represent atomic magnetic dipoles. Within each domain, all dipoles are aligned, whereas the direction of alignment varies from one domain to another [12].

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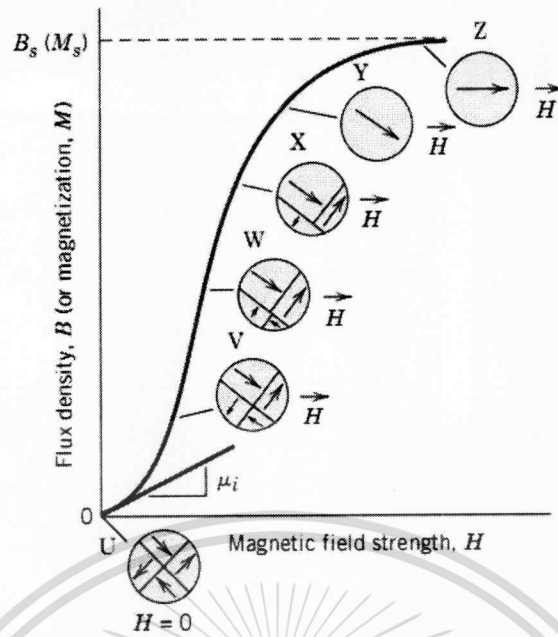




**Figure 2.19** The gradual change in magnetic dipole orientation across a domain wall [12].

Flux density  $B$  and field intensity  $H$  are not proportional for ferromagnets and ferrimagnets. If the material is initially unmagnetized, then  $B$  varies as a function of  $H$  as shown in **Figure 2.20**. The curve begins at the origin. As  $H$  is increased, the  $B$  field begins to increase slowly, then more rapidly, finally becoming independent of  $H$ . This maximum value of  $B$  is the saturation flux density  $B_s$ , and the corresponding magnetization is the saturation magnetization  $M_s$ , mentioned previously. Since the permeability  $\mu$  from **Equation 2.4** is the slope of the  $B$ -versus- $H$  curve, note from **Figure 2.17** that the permeability changes with and independent on  $H$ . On occasion, the slope of the  $B$ -versus- $H$  curve at  $H = 0$  is specified as a material property, which is termed the *initial permeability*  $\mu_i$ , as indicated in **Figure 2.20** [12].

As an  $H$  field is applied, the domains change shape and size by the movement of domain boundaries. Schematic domain structures are represented in the insets (labeled U through Z) at several points along the  $B$ -versus- $H$  curve in **Figure 2.20**. Initially, the moments of the constituent domains are randomly oriented such that there is no net  $B$  (or  $H$ ) field (inset U). As the external field is applied, the domains that are oriented in directions favorable to (or nearly aligned with) the applied field grow at the expense of those that are unfavorably oriented (inset V through X). This process continues with increasing field strength until the macroscopic specimen becomes a single domain, which is nearly aligned with the field (inset Y). Saturation is achieved when this domain, by means of rotation, becomes oriented with the  $H$  field (inset Z).



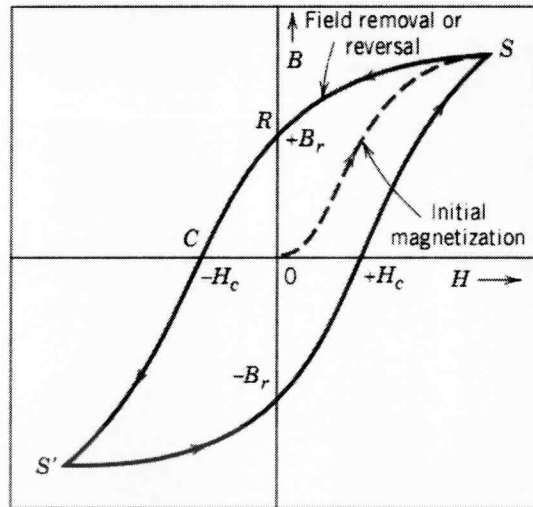
**Figure 2.20**  $B$ -versus- $H$  behavior for a ferromagnetic of ferromagnetic material that was initially unmagnetized. Domain configurations during several stages of magnetization are represented. Saturation flux density  $B_s$ , magnetization  $M_s$ , and initial permeability  $\mu_i$  are also indicated [12].

#### 2.4.2.1 Remanence

A hysteresis effect is produced in which the  $B$  field lags behind the applied  $H$  field, or decreases at a lower rate. From saturation, point  $S$  in **Figure 2.21**, as the  $H$  field is reduced by reversal of field direction, the curve does not retrace its original path. At zero  $H$  field (point  $R$  on the curve), there exists a residual  $B$  field that is called the remanence, or remanent flux density,  $B_r$ ; the material remains magnetized in the absence of an external  $H$  field [12].

Hysteresis behavior and permanent magnetization may be explained by the motion of domain walls. Upon reversal of the field direction from saturation (point  $S$  in **Figure 2.21**), the process by which the domain structure changes is reversed. First, there is a rotation of the single domain with the reversed field. Next, domains having magnetic moments aligned with the new field form and grow at the expense of the former domains. Critical to this explanation is the resistance to movement of domain walls that occurs in response to the increase of the magnetic field in the opposite direction; this accounts for the lag of  $B$  with  $H$ , or the hysteresis. When the applied field reaches zero, there is still some net volume fraction of domains oriented in the former direction, which explains the existence of the remanence  $B_r$ .



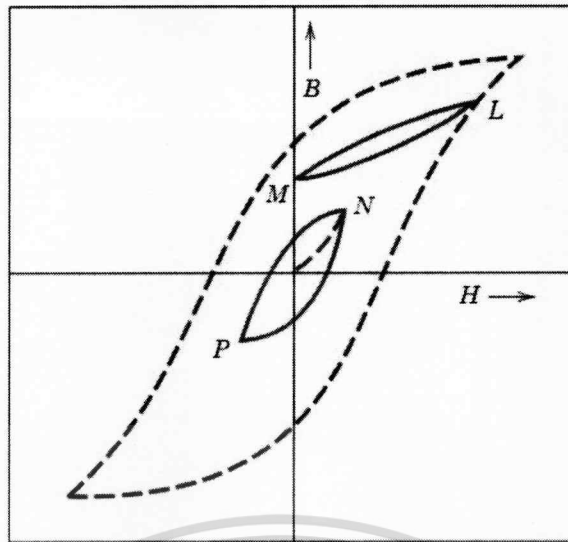


**Figure 2.21** Magnetic flux density versus the magnetic field strength for a ferromagnetic material that is subjected to forward and reverse saturations (points  $S$  and  $S'$ ). The hysteresis loop is represented by the solid curve; the dashed curve indicates the initial magnetization. The remanence  $B_r$  and the coercive force  $H_c$  are also shown [12].

#### 2.4.2.2 Coercivity

To reduce the  $B$  field within the specimen to zero (point  $C$  on **Figure 2.21**), an  $H$  field of magnitude  $-H_c$  must be applied in a direction opposite to that of the original field;  $H_c$  is called the coercivity, or sometimes the coercive force. Upon continuation of the applied field in this reverse direction, as indicated in the figure, saturation is ultimately achieved in the opposite sense, corresponding to point  $S'$ . A second reversal of the field to the point of the initial saturation (point  $S$ ) completes the symmetrical hysteresis loop and also yields both a negative remanence ( $-B_r$ ) and a positive coercivity ( $+H_c$ ) [12].

The  $B$ -versus- $H$  curve in **Figure 2.21** represents a hysteresis loop taken to saturation. It is not necessary to increase the  $H$  field to saturation before reversing the field direction; in **Figure 2.22**, loop  $NP$  is a hysteresis curve corresponding to less than saturation. Furthermore, it is possible to reverse the direction of the field at any point along the curve and generate other hysteresis loops. One such loop is indicated on the saturation curve in **Figure 2.22**: for loop  $LM$ , the  $H$  field is reversed to zero. One method of demagnetizing a ferromagnet or ferrimagnet is to repeatedly cycle it in an  $H$  field that alternates direction and decreases in magnitude [12].



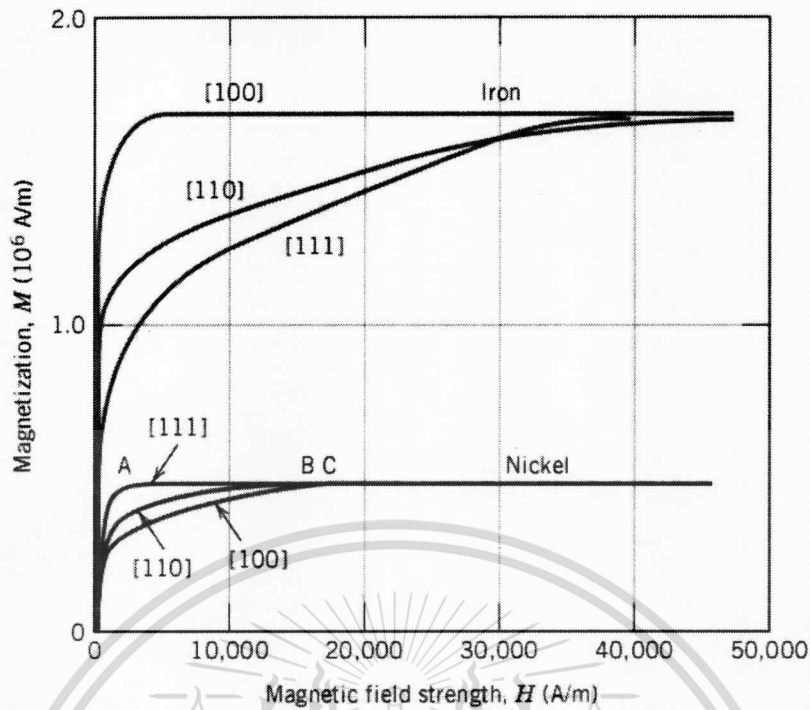
**Figure 2.22** A hysteresis curve at less than saturation (curve  $NP$ ) within the saturation loop for a ferromagnetic material. The  $B$ - $H$  behaviour for field reversal at other than saturation is indicated by curve  $LM$  [12].

#### 2.4.3 Hysteresis Characteristics

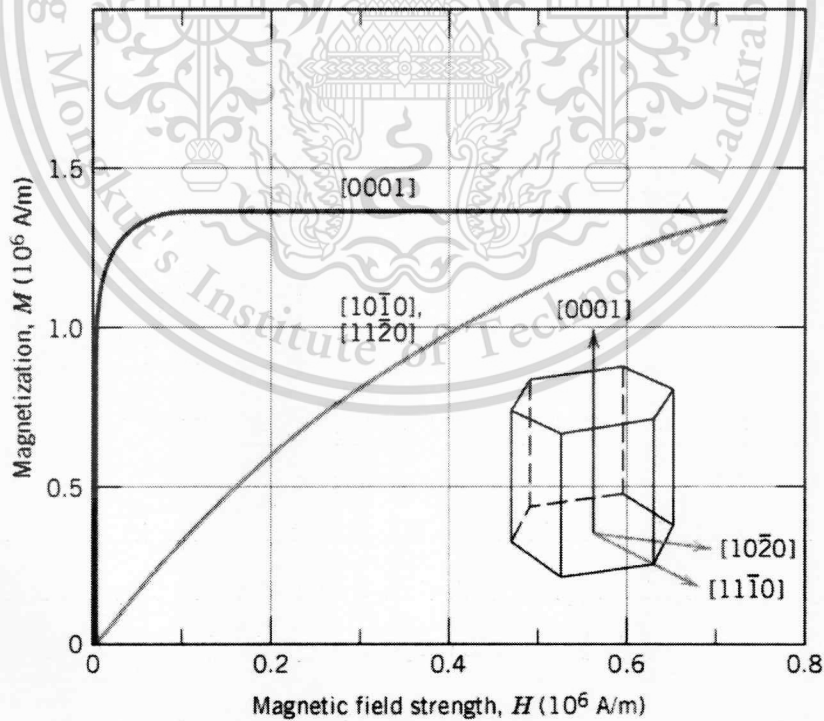
The magnetic hysteresis curves will have different shapes depending on various factors: (1) whether the specimen is a single crystal or polycrystalline; (2) if polycrystalline, any preferred orientation of the grains; (3) the presence of pores or second-phase particles; and (4) other factors such as temperature and, if a mechanical stress is applied, the stress state [12].

For example, the  $B$  (or  $M$ ) versus  $H$  curve for a single crystal of a ferromagnetic material depends on its crystallographic orientation relative to the direction of the applied  $H$  field. This behaviour is demonstrated in **Figure 2.23** for single crystals of nickel (FCC) and iron (BCC), where the magnetizing field is applied in  $[100]$ ,  $[110]$ , and  $[111]$  crystallographic directions; and in **Figure 2.24** for cobalt (HCP) in  $[0001]$  and  $[1010]/[1120]$  directions. This dependence of magnetic behaviour on crystallographic orientation is termed *magnetic* (or sometimes *magnetocrystalline*) *anisotropy*.





**Figure 2.23** Magnetization curves for single crystals of iron and nickel. For both metals, a different curve was generated when the magnetic field was applied in each of [100], [110], and [111] crystallographic directions [12].



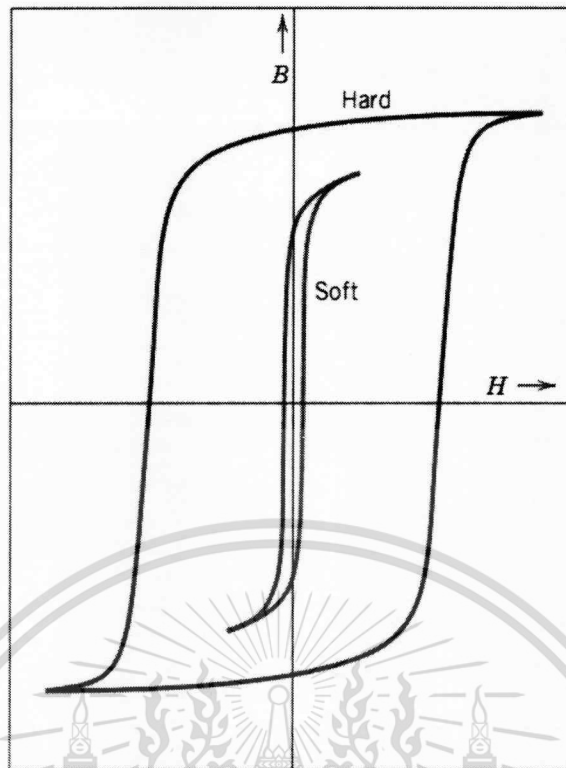
**Figure 2.24** Magnetization curves for single crystals of cobalt. The curves were generated when the magnetic field was applied in [0001] and [1010]/[1120] crystallographic directions [12].

For each of these materials there is one crystallographic direction in which magnetization is easiest—that is, saturation (of  $M$ ) is achieved at the lowest  $H$  field; this is termed a direction of *easy magnetization*. For example, for Ni (**Figure 2.23**) this direction is  $[111]$  inasmuch as saturation occurs at point A; whereas, for  $[110]$  and  $[100]$  orientations, saturation points correspond, respectively, to points B and C. Correspondingly, easy magnetization directions for Fe and Co are  $[100]$  and  $[0001]$ , respectively (**Figure 2.23** and **Figure 2.24**). Conversely, a *hard* crystallographic direction is that direction for which saturation magnetization is most difficult; hard directions for Ni, Fe, and Co are  $[100]$ ,  $[111]$ , and  $[1010]/[1120]$ .

#### 2.4.3.1 Soft Magnetic Materials

Both ferromagnetic and ferromagnetic materials are classified as either soft or hard on the basis of their hysteresis characteristics. Soft magnetic materials are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low; one familiar example consists of transformer cores. For this reason the relative area within the hysteresis loop must be small; it is characteristically thin and narrow, as represented in **Figure 2.25**. Consequently, a soft magnetic material must have a high initial permeability and low coercivity. A material possessing these properties may reach its saturation magnetization with a relatively low applied field (i.e., is easily magnetized and demagnetized) and still has low hysteresis energy losses [12].

The saturation field or magnetization is determined only by the composition of the material. For example, in cubic ferrites, substitution of a divalent metal ion such as  $\text{Ni}^{2+}$  for  $\text{Fe}^{2+}$  in  $\text{FeO-Fe}_2\text{O}_3$  will change the saturation magnetization. However, susceptibility and coercivity ( $H_c$ ), which also influence the shape of the hysteresis curve, are sensitive to structural variables rather than to composition. For example, a low value of coercivity corresponds to the easy movement of domain walls as the magnetic field changes magnitude and/or direction. Structural defects such as particles of a nonmagnetic phase or voids in the magnetic material tend to restrict the motion of domain walls, and thus increase the coercivity. Consequently, a soft magnetic material must be free of such structural defects [12].



**Figure 2.25** Schematic magnetization curves for soft and hard magnetic materials [12].

Another property consideration for soft magnetic materials is electrical resistivity. In addition to the hysteresis energy losses described above, energy losses may result from electrical currents that are induced in a magnetic material by a magnetic field that varies in magnitude and direction with time; these are called *eddy currents*. It is most desirable to minimize these energy losses in soft magnetic materials by increasing the electrical resistivity. This is accomplished in ferromagnetic materials by forming solid solution alloys; iron-silicon and iron-nickel alloys are examples. The ceramic ferrites are commonly used for applications requiring soft magnetic materials because they are intrinsically electrical insulators. Their applicability is somewhat limited, however, inasmuch as they have relatively small susceptibilities. The properties of a half-dozen soft magnetic materials are shown in **Table 2.4**.



**Table 2.4** Typical properties for several soft magnetic materials [12].

| Material                   | Composition<br>(wt %)                                                      | Initial Relative<br>Permeability<br>$\mu_i$ | Saturation<br>Flux Density<br>$B_s$ [tesla] | Hysteresis<br>Loss/Cycle<br>[J/m <sup>3</sup> ] | Resistivity<br>$\rho$ ( $\Omega\cdot m$ ) |
|----------------------------|----------------------------------------------------------------------------|---------------------------------------------|---------------------------------------------|-------------------------------------------------|-------------------------------------------|
| Commercial<br>iron ingot   | 99.95Fe                                                                    | 150                                         | 2.14                                        | 270                                             | $1.0 \times 10^{-7}$                      |
| Silicon-iron<br>(oriented) | 97Fe, 3Si                                                                  | 1,400                                       | 2.01                                        | 40                                              | $4.7 \times 10^{-7}$                      |
| 45 Permalloy               | 55Fe, 45Ni                                                                 | 2,500                                       | 1.60                                        | 120                                             | $4.5 \times 10^{-7}$                      |
| Superalloy                 | 79Ni, 15Fe,<br>5Mo, 0.5Mn                                                  | 75,000                                      | 0.80                                        | —                                               | $6.0 \times 10^{-7}$                      |
| Ferroxcube A               | 48MnFe <sub>2</sub> O <sub>4</sub> ,<br>52ZnFe <sub>2</sub> O <sub>4</sub> | 1,400                                       | 0.33                                        | ~40                                             | 2000                                      |
| Ferroxcube B               | 36NiFe <sub>2</sub> O <sub>4</sub> ,<br>64ZnFe <sub>2</sub> O <sub>4</sub> | 650                                         | 0.36                                        | ~35                                             | 10 <sup>7</sup>                           |

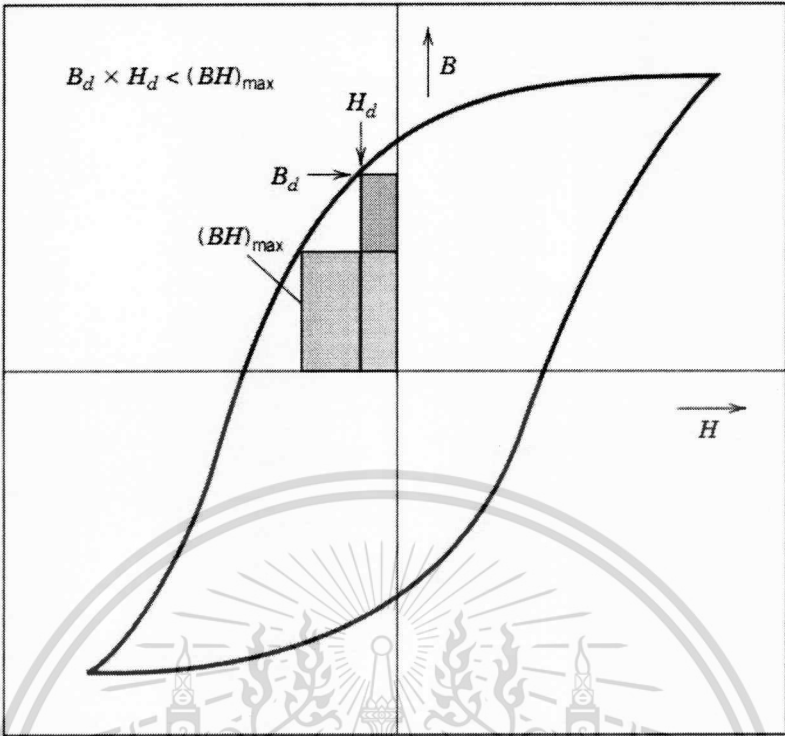
The hysteresis characteristics of soft magnetic materials may be enhanced for some applications by an appropriate heat treatment in the presence of a magnetic field. Using such a technique, a square hysteresis loop may be produced, which is desirable in some magnetic amplifier and pulse transformer applications. In additions, soft magnetic materials are used in generators, motors, dynamos, and switching circuits [12].

**2.4.3.2 Hard Magnetic Materials**

Hard magnetic materials are utilized in permanent magnets, which must have a high resistance to demagnetization. In terms of hysteresis behaviour, a hard magnetic material has a high remanence, coercivity, and saturation flux density, as well as a low initial permeability, and high hysteresis energy losses. The hysteresis characteristics for hard and soft magnetic materials are compared in **Figure 2.25**. The two most important characteristics, related to applications for these materials, are the coercivity and the energy product, designated as  $(BH)_{max}$ . This  $(BH)_{max}$  corresponds to the area of the largest  $B$ - $H$  rectangle that can be constructed within the second quadrant of the hysteresis curve, **Figure 2.26**; its units are  $\text{kJ/m}^3$  (MGOe). The value of the energy product is representative of the energy required to demagnetize a permanent magnet; that is, the larger  $(BH)_{max}$  the harder is the material in terms of its magnetic characteristics [12].

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**Figure 2.26** Schematic magnetization curve that displays hysteresis. Within the second quadrant are drawn two  $B$ - $H$  energy product rectangles; the area of that rectangle labeled  $(BH)_{\max}$  is the largest possible, which is greater than the area defined by  $B_d$ - $H_d$  [12].

Hysteresis behavior is related to ease with which the magnetic domain boundaries move; by impeding domain wall motion, the coercivity and susceptibility are enhanced, such that a large external field is required for demagnetization. Furthermore, these characteristics are interrelated to the microstructure of the material [12].

**2.4.4 Neodymium-type Magnets**

Neodymium magnet, the type of rare-earth magnet, is a permanent magnet made from an alloy of neodymium, iron, and boron to form the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  tetragonal crystalline structure. Neodymium magnet was developed by General Motors and Sumimoto Special Metals since 1982. It replaces other types of magnet in many applications in modern products that require strong permanent magnets. Since the development of Nd-Fe-B, there are many researches on this type of permanent magnets [13-29]. The fabrication routes, given in **Figure 2.27**, can be used to categorize these magnets: polymer bonding [15-19], sintering [20-24] and hot deformed. The comparison of fabrication routes are shown in **Table 2.5**.

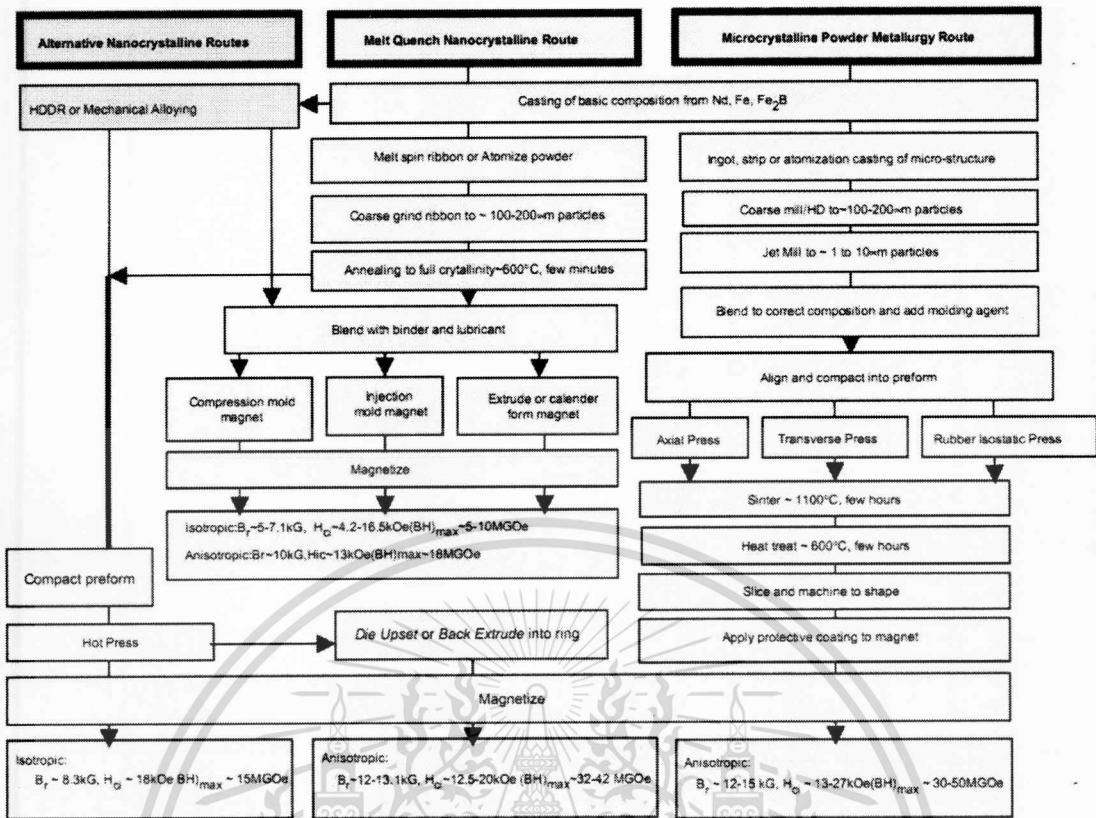


Figure 2.27 Basic schematic for common magnet production routes [13].

Common themes of improvement for NdFeB magnets: higher maximum energy product, improved environmental stability and corrosion resistance at elevated operating temperatures, near-net-shape manufacture, improved magnetization behavior [13].

Table 2.5 Comparison of three fabrication routes [13].

| Type                 | Density       | Energy Product | Near-net-shape      |
|----------------------|---------------|----------------|---------------------|
| Sintered magnets     | Full density  | High           | Simple shape        |
| Bonded magnets       | Lower density | Intermediate   | Intricate net-shape |
| Hot deformed magnets | Full density  | High           | Net-shape           |

2.4.4.1 Bonded Magnets

Bonded magnets are prepared by melt spinning ribbon, which its composition is close to Nd<sub>2</sub>Fe<sub>14</sub>B. This ribbon is subsequently crushed into a powder then blended with polymer and form into a magnet. Other than melt spinning, nanograin material can be produced by atomization, hydrogen disproportionation desorption recombination (HDDR) and mechanically alloying [13]. The process to produce bonded magnet is very simple. After melt spinning, the materials were



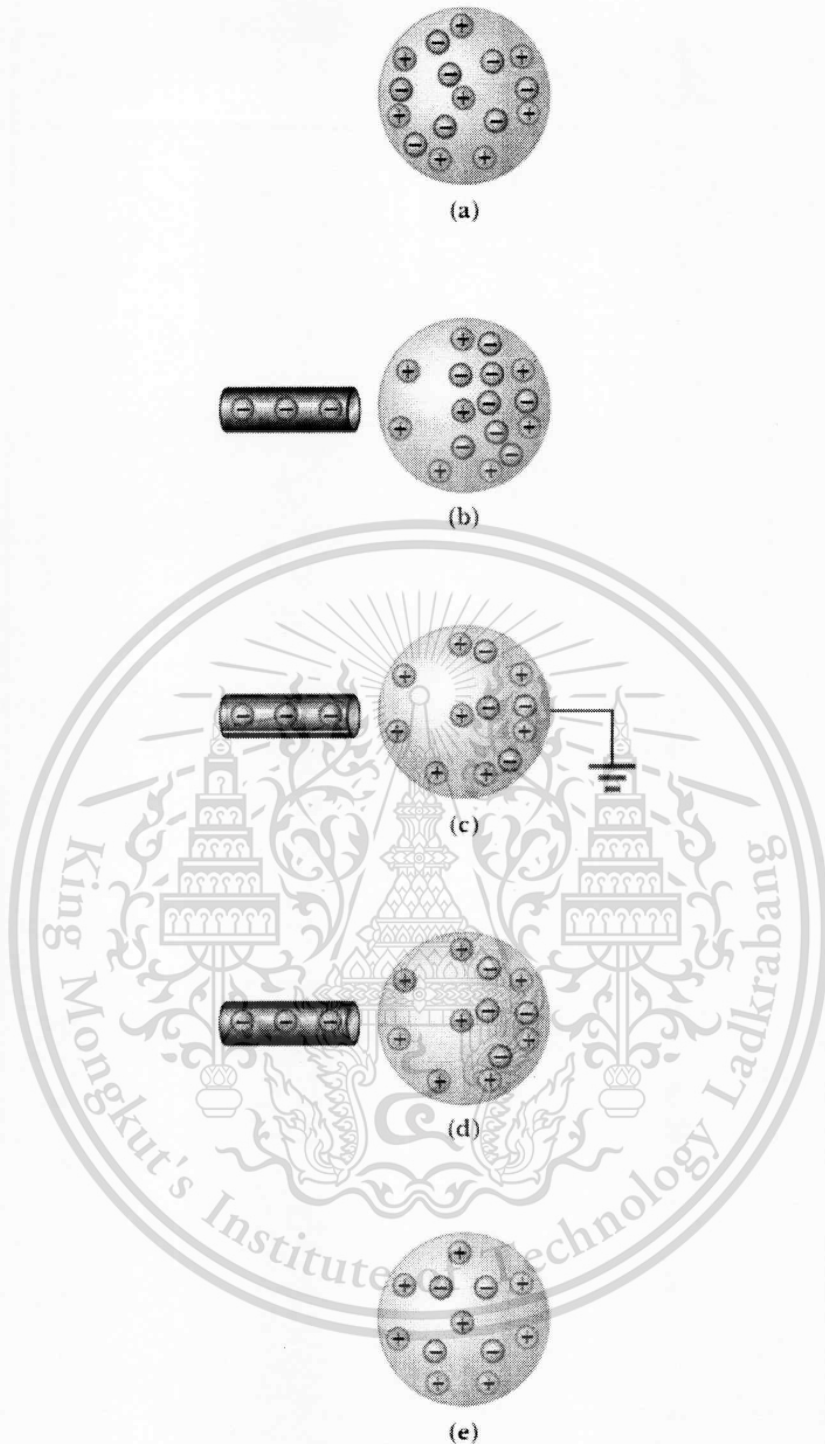
blended with binder and press by compaction mould. Then put in a furnace environment of 170 degree of Celsius for 20 minutes. The final stage is to magnetize by magnetizer.

#### 2.4.4.2 Sintered Magnets

Sintered magnets are prepared by the raw materials being melt in a furnace, cast into a mould and cooled to form ingots. The ingots are pulverized and milled to tiny particles. Conventionally, green compacts for sintered magnets have been aligned and pressed in a magnetic field, which is either parallel or perpendicular to the axis of pressing [13].

### 2.5 Electricity and Magnetism

An induction process is shown in **Figure 2.28a**. There are an equal number of electrons and protons in the sphere if the charge on the sphere is exactly zero. When a negatively charged rubber rod is brought near the sphere, electrons in the region nearest the rod experience a repulsive force and migrate to the opposite side of the sphere. This leaves the side of the sphere near the rod with an effective positive charge because of the diminished number of electrons, as in **Figure 2.28b**. This occurs even if the rod never actually touches the sphere. If the same experiment is performed with a conducting wire connected from the sphere to the Earth (**Figure 2.28c**), some of the electrons in the conductor are so strongly repelled by the presence of the negative charge in the rod that they move out of the sphere through the wire and into the Earth. If the wire to ground is then removed (**Figure 2.28d**), the conducting sphere contains an excess of induced positive charge because it has fewer electrons than it needs to cancel out the positive charge of the protons. When the rubber rod is removed from the vicinity of the sphere (**Figure 2.28e**), this induced positive charge remains on the ungrounded sphere. Note that the rubber rod loses none of its negative charge during this process [30].



**Figure 2.28** Charging a metallic object by induction (that is, the two objects never touch each other). (a) A neutral metallic sphere, with equal numbers of positive and negative charges. (b) The electrons on the neutral sphere are redistributed when a charged rubber rod is placed near the sphere. (c) When the sphere is grounded, some of its electrons leave through the ground wire. (d) When the ground connection is removed, the sphere has excess positive charge that is nonuniformly distributed. (e) When the rod is removed, the remaining electrons redistribute uniformly and there is a net uniform distribution of positive charge on the sphere [30].

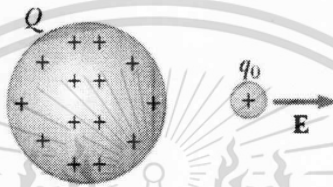
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### 2.5.1 Electric Fields

The gravitational force and the electric force—field forces can act through space, producing an effect even when no physical contact occurs between interacting objects. The gravitational field  $g$  at a point in space was defined to be equal to the gravitational force  $F_g$  acting on a test particle of mass divided by that mass:  $g = F_g/m$ . The concept of a field was developed by Michael Faraday (1791-1867), in the context of electric forces. In this approach, an electric field exists in the region of space around a charged object, the source charge. When another charged object, the test charge, enters this electric field, an electric force acts on it [30].



**Figure 2.29** A small positive test charge  $q_0$  placed near an object carrying a much larger positive charge  $Q$  experiences an electric field  $\mathbf{E}$  directed as shown [30].

A small positive test charge  $q_0$  placed near a second object carrying a much greater positive charge  $Q$  is shown **Figure 2.29**. The electric field due to the source charge at the location of the test charge is equal to the electric force on the test charge *per unit charge*, or to be more specific **the electric field vector  $\mathbf{E}$**  at a point in space is defined as the electric force  $\mathbf{F}_e$  acting on a positive test charge placed at that point divided by the test charge:

$$\mathbf{E} = \frac{\mathbf{F}_e}{q_0} \quad (2.25)$$

Note that  $\mathbf{E}$  is the field produced by some charge or charge distribution separate from the test charge, it is not the field produced by the test charge itself. Also, note that the existence of an electric field is a property of its source, the presence of the test charge is not necessary for the field to exist. The test charge serves as a *detector* of the electric field.

**Equation 2.25** can be rearranged as

$$\mathbf{F}_e = q\mathbf{E} \quad (2.26)$$

This equation illustrates the force on a charged particle placed in an electric field. If  $q$  is positive, the force is in the same direction as the field. If  $q$  is negative, the force and the field are in opposite directions.

### 2.5.1.1 Coulomb's Law

Charles Coulomb (1736-1806) measured the magnitudes of the electric forces between charged objects using the torsion balance which he invented. Coulomb confirmed that the electric force between two small charged spheres is proportional to the inverse square of their separation distance  $r$ —that is,  $F_e \propto 1/r^2$  [30].

The coulomb force can be expressed as the following equation:

$$F_e = k_e \frac{|q_1||q_2|}{r^2} \quad (2.27)$$

Where  $k_e$  is a constant called the **Coulomb constant**. In his experiments, Coulomb was able to show that the value of the exponent of  $r$  was 2 to within an uncertainty of a few percent. Modern experiments have shown that the exponent is 2 within an uncertainty of a few parts in  $10^{16}$ .

The value of the Coulomb constant depends on the choice of units. The SI unit of charge is the **coulomb** (C). The Coulomb constant  $k_e$  in SI units has the value

$$k_e = 8.9875 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \quad (2.28)$$

This constant is also written in the form

$$k_e = \frac{1}{4\pi\epsilon_0} \quad (2.29)$$

Where the constant  $\epsilon_0$  (lowercase Greek epsilon) is known as the **permittivity of free space** and has the value

$$\epsilon_0 = 8.8542 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2 \quad (2.30)$$

The smallest unit of charge  $e$  known in nature is the charge on an electron ( $-e$ ) or a proton ( $+e$ ) and has a magnitude

$$e = 1.60219 \times 10^{-19} \text{ C} \quad (2.31)$$

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The charges and masses of the electron, proton, and neutron are given in **Table 2.6**.

**Table 2.6** Charge and mass of the electron, proton, and neutron [30].

| Particle     | Charge (C)                   | Mass (kg)                 |
|--------------|------------------------------|---------------------------|
| Electron (e) | $-1.6021917 \times 10^{-19}$ | $9.1095 \times 10^{-31}$  |
| Proton (p)   | $+1.6021917 \times 10^{-19}$ | $1.67261 \times 10^{-27}$ |
| Neutron (n)  | 0                            | $1.67492 \times 10^{-27}$ |

2.5.1.2 Electric Field Lines

A test charge  $q_0$  is placed at point  $P$ , a distance  $r$  from the source charge, as in **Figure 2.30a**. The test charge was used to determine the direction of the electric force and the electric field. However, the electric field does not depend on the existence of the test charge, it is established solely by the source charge. According to Coulomb’s law, the force exerted by  $q$  on the test charge is

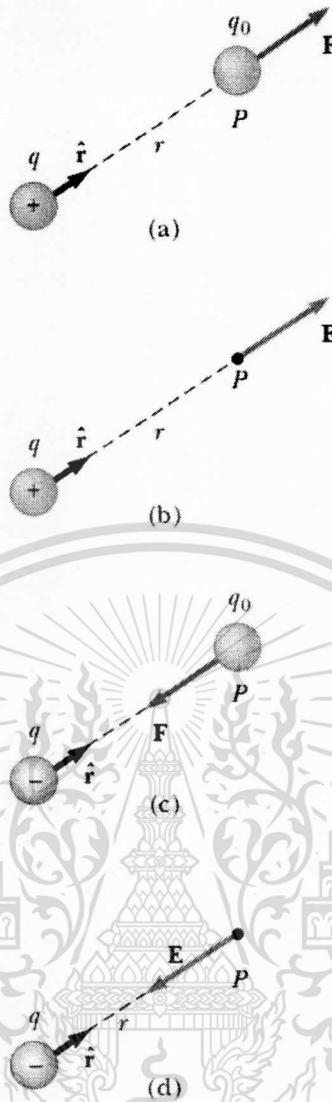
$$\mathbf{F}_e = k_e \frac{qq_0}{r^2} \hat{\mathbf{r}} \tag{2.32}$$

Where  $\hat{\mathbf{r}}$  is a unit vector directed from  $q$  toward  $q_0$ . This force in **Figure 2.30a** is directed away from the source charge  $q$ . The electric field at point  $P$  is created by  $q$ , shown in the following equation:

$$\mathbf{E} = k_e \frac{q}{r^2} \hat{\mathbf{r}} \tag{2.33}$$

If the source charge  $q$  is positive, **Figure 2.30b** shows the situation with the test charge removed—the source charge sets up an electric field at point  $P$ , directed away from  $q$ . If  $q$  is negative, as in **Figure 2.30c**, the force on the test charge is toward the source charge, so the electric field at  $P$  is directed toward the source charge, as in **Figure 2.30d**.





**Figure 2.30** A test charge  $q_0$  at point  $P$  is a distance  $r$  from a point charge  $q$ . (a) If  $q$  is positive, then the force on the test charge is directed away from  $q$ . (b) For the positive source charge, the electric field at  $P$  points radially outward from  $q$ . (c) If  $q$  is negative, then the force on the test charge is directed toward  $q$ . (d) For the negative source charge, the electric field at  $P$  points radially inward toward  $q$  [30].

The total electric field due to a group of source charges at any point  $P$  is equal to the vector sum of the electric fields of all the charges.

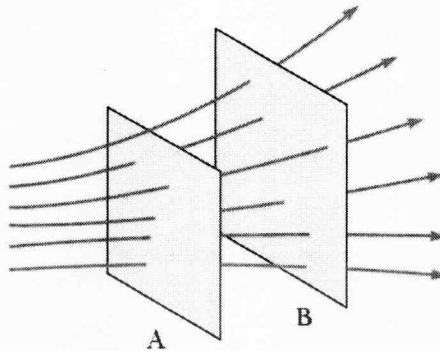
This superposition principle applied to fields follows directly from the superposition property of electric forces. Thus, the electric field at point  $P$  due to a group of source charges can be expressed as the vector sum

$$\mathbf{E} = k_e \sum_i \frac{q_i}{r_i^2} \hat{\mathbf{r}}_i \quad (2.34)$$

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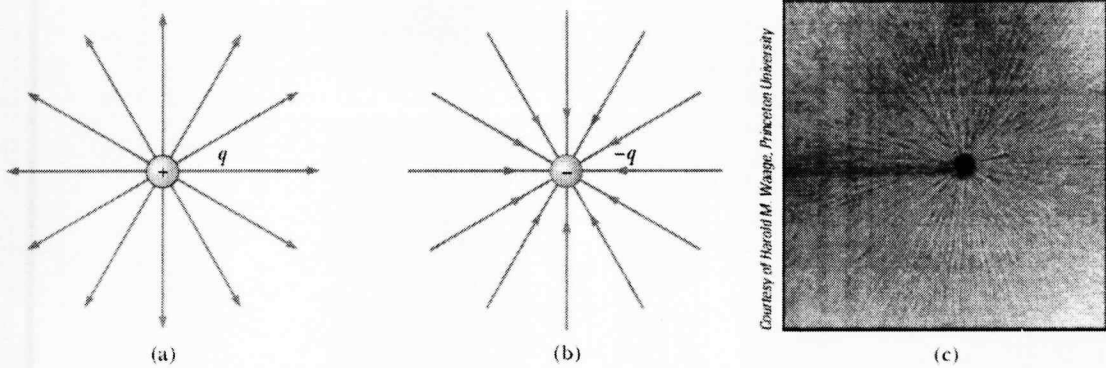
Where  $r_i$  is the distance from the  $i$ th source charge  $q_i$  to the point  $P$  and  $\hat{r}_i$  is a unit vector directed from  $q_i$  toward  $P$ .



**Figure 2.31** Electric field lines penetrating two surfaces. The magnitude of the field is greater on surface A than on surface B [30].

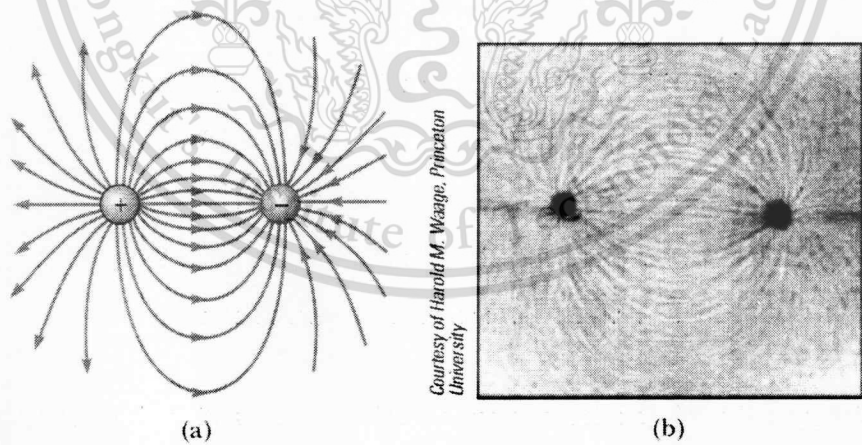
These properties are illustrated in **Figure 2.31**. The density of lines through surface A is greater than the density of lines through surface B. Therefore, the magnitude of electric field is larger on surface A than on surface B. Furthermore, the fact that the lines at different locations point in different directions indicates that the field is nonuniform.

Representative electric field lines for the field due to a single positive point charge are shown in **Figure 2.32a**. This two-dimensional drawing shows only the field lines that lie in the plane containing the point charge. The lines are actually directed radially outward from the charge in all directions. Because a positive test charge placed in this field would be repelled by the positive source charge, the lines are directed radially away from the source charge. The electric field lines representing the field due to a single negative point charge are directed toward the charge (**Figure 2.32b**). In either case, the lines are along the radial direction and extend all the way to infinity. Note that the lines become closer together as they approach the charge; this indicates that the strength of the field increases as we move toward the source charge [30].



**Figure 2.32** The electric field lines for a point charge. (a) For a positive point charge, the lines are directed radially outward. (b) For a negative point charge, the lines are directed radially inward. Note that the figures show only those field lines that lie in the plane of the page. (c) The dark areas are small pieces of thread suspended in oil, which align with the electric field produced by a small charged conductor at the center [32].

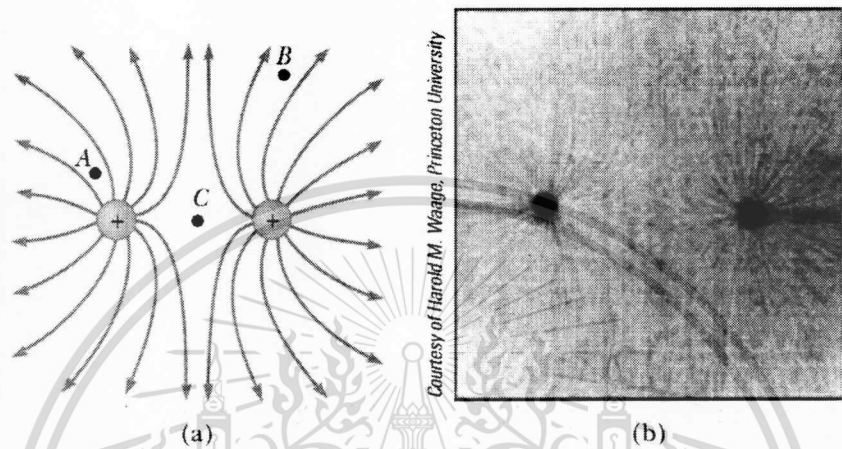
The electric field lines for two point charges of equal magnitude but opposite signs (an electric dipole) are shown in **Figure 2.33**. Because the charges are of equal magnitude, the number of lines that begin at the positive charge must equal the number that terminate at the negative charge. At points very near the charges, the lines are nearly radial. The high density of lines between the charges indicates a region of strong electric field [30].



**Figure 2.33** (a) The electric field lines for two point charges of equal magnitude and opposite sign (an electric dipole). The number of lines leaving the positive charge equals the number terminating at the negative charge. (b) The dark lines are small pieces of thread suspended in oil, which align with the electric field of a dipole [30].

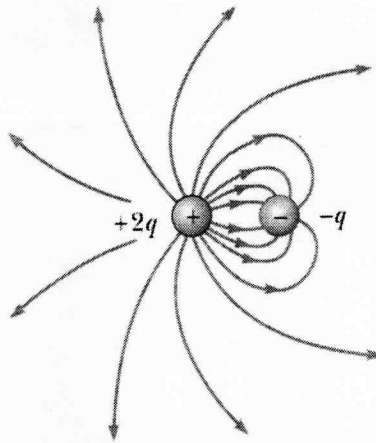


The electric field lines in the vicinity of two equal positive point charges are shown in **Figure 2.34**. Thus, the lines are nearly radial at points close to either charge, and the same number of lines emerge from each charge because the charges are equal in magnitude. At great distances from the charges, the field is approximately equal to that of a single point charge of magnitude  $2q$ .



**Figure 2.34** (a) The electric field lines for two positive point charges. (b) Pieces of thread suspended in oil, which align with the electric field created by two equal-magnitude positive charges [30].

Finally, the electric field lines associated with a positive charge  $+2q$  and a negative charge  $-q$  is illustrated in **Figure 2.35**. In this case, the number of lines leaving  $+2q$  is twice the number terminating at  $-q$ . Hence, only half of the lines that leave the positive charge reach the negative charge. The remaining half terminate on a negative charge we assume to be at infinity. At distances that are much greater than the charge separation, the field lines are equivalent to those of a single charge  $+q$ .



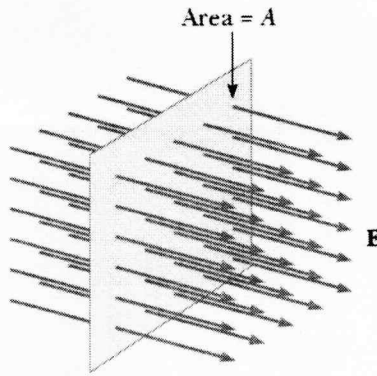
**Figure 2.35** The electric field lines for a point charges  $+2q$  and a second point charge  $-q$ . Note that two lines leave  $+2q$  for every one that terminates on  $-q$  [30].

## 2.5.2 Gauss's Law

The fundamental electrostatic force between point charges exhibits an inverse-square behaviour. Although a consequence of Coulomb's law, Gauss's law is more convenient for calculating the electric fields of highly symmetric charge distributions and makes possible useful qualitative reasoning when dealing with complicated problems [30].

### 2.5.2.1 Electric Flux

An electric field that is uniform in both magnitude and direction is shown in **Figure 2.36**. The field lines penetrate a rectangular surface of area  $A$ , whose plane is oriented perpendicular to the field. The number of lines per unit area (in other words, the *line density*) is proportional to the magnitude of the electric field. Hence, the total number of lines penetrating the surface is proportional to the product  $EA$ . This product of the magnitude of the electric field  $E$  and surface area  $A$  perpendicular to the field is called the **electric flux**  $\Phi_E$  (uppercase Greek phi):

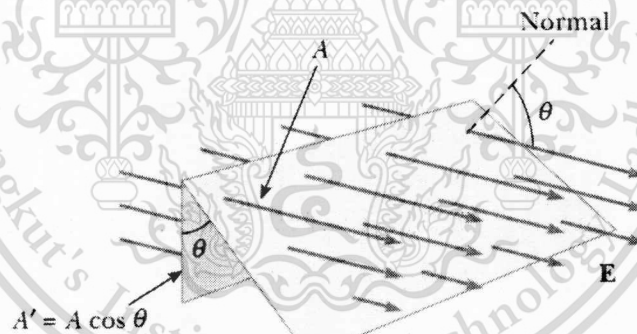


**Figure 2.36** Field lines representing a uniform electric field penetrating a plane of area  $A$  perpendicular to the field. The electric flux  $\Phi_E$  through this area is equal to  $EA$  [30].

$$\Phi_E = EA$$

(2.35)

From the SI units  $E$  of and  $A$ ,  $\Phi_E$  has units of newton-meters squared per coulomb ( $\text{N} \cdot \text{m}^2/\text{C}$ ). Electric flux is proportional to the number of electric field lines penetrating some surface.



**Figure 2.37** Field lines representing a uniform electric field penetrating an area  $A$  that is at an angle  $\theta$  to the field. Because the number of lines that go through the area  $A'$  is the same as the number that go through  $A$ , the flux through  $A'$  is equal to the flux through  $A$  and is given by

$$\Phi_E = EA \cos \theta \text{ [30].}$$

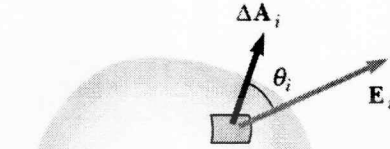
If the surface under consideration is not perpendicular to the field (see **Figure 2.37**), the flux through it must be less than that given by **Equation 2.35**. Note that the number of lines that cross this area  $A$  is equal to the number that cross the area  $A'$ , which is a projection of area  $A$  onto a plane oriented perpendicular to the field. From **Figure 2.37**, the two areas are related by  $A' = A \cos \theta$ . The flux through  $A$  equals the flux through  $A'$ , thus the flux through  $A$  is

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$$\Phi_E = EA' = EA \cos \theta \quad (2.36)$$

The flux through a surface of fixed area  $A$  has a maximum value  $EA$  when the surface is perpendicular to the field ( $\theta = 90^\circ$ ). But when the surface is parallel to the field, the flux is zero ( $\theta = 0^\circ$ ).



**Figure 2.38** A small element of surface area  $\Delta A_i$ . The electric field makes an angle  $\theta_i$  with the vector  $\Delta A_i$ , defined as being normal to the surface element, and the flux through the element is equal to  $E_i \Delta A_i \cos \theta_i$  [30].

In general, the electric field may vary over a surface. Therefore, the flux given by **Equation 2.36** responses only to a small element of area. A general surface divided up into a large number of small elements, each of area  $\Delta A$ . The variation in the electric field over one element can be neglected if the element is sufficiently small. It is convenient to define a vector  $\Delta \mathbf{A}_i$  whose magnitude represents the area of the  $i$ th element of the surface and whose direction is defined to be *perpendicular* to the surface element, as shown in **Figure 2.38**. The electric field  $\mathbf{E}_i$  at the location of this element makes an angle  $\theta_i$  with the vector  $\Delta \mathbf{A}_i$ . The electric flux  $\Delta \Phi_E$  through this element is

$$\Delta \Phi_E = E_i \Delta A_i \cos \theta_i = \mathbf{E}_i \cdot \Delta \mathbf{A}_i \quad (2.37)$$

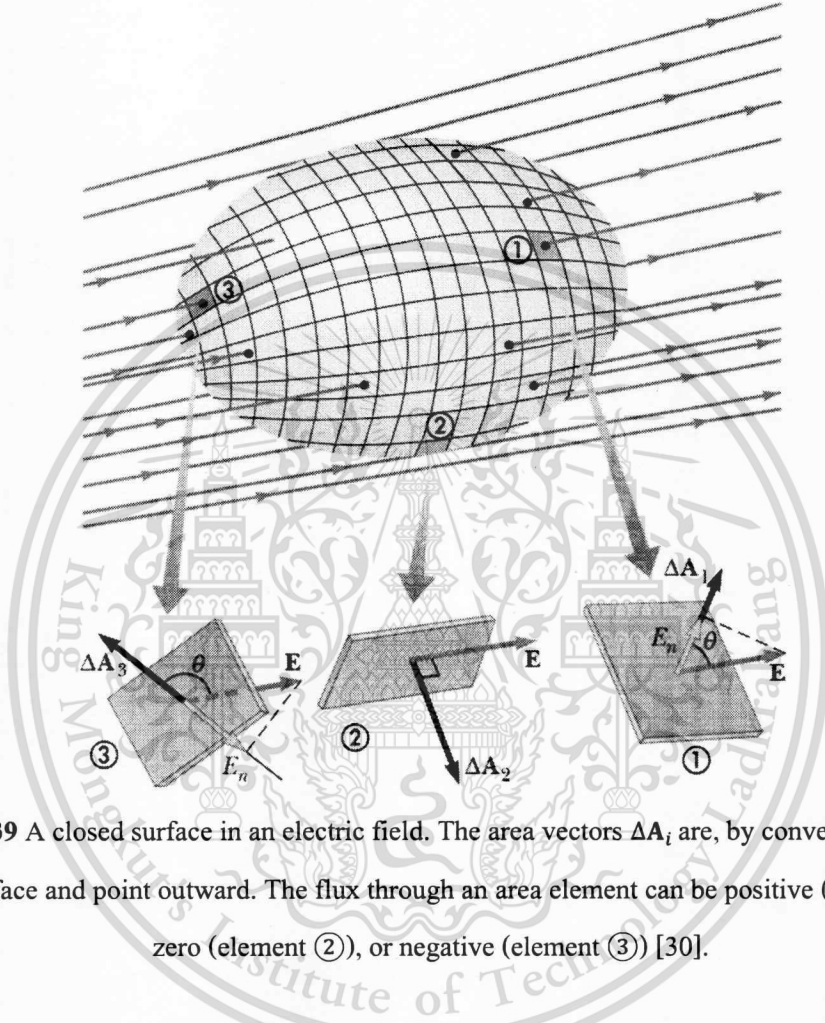
Where the definition of the scalar product (or dot product) of two vectors is  $\mathbf{A} \cdot \mathbf{B} = AB \cos \theta$ . By summing the contributions of all elements, the total flux through the surface is obtained. If letting the area of each element approach zero, then the number of elements approaches infinity and the sum is replaced by an integral. Therefore, the general definition of electric flux is

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$$\Phi_E = \lim_{\Delta A_i \rightarrow 0} \sum \mathbf{E}_i \cdot \Delta \mathbf{A}_i = \int_{\text{surface}} \mathbf{E} \cdot d\mathbf{A} \quad (2.38)$$

**Equation 2.38** is a surface integral, the value of  $\Phi_E$  depends both on the field pattern and on the surface.



**Figure 2.39** A closed surface in an electric field. The area vectors  $\Delta \mathbf{A}_i$  are, by convention, normal to the surface and point outward. The flux through an area element can be positive (element ①), zero (element ②), or negative (element ③) [30].

The flux is divided into inside and outside region, and one cannot move from one region to the other without crossing the closed surface.

The vectors  $\Delta \mathbf{A}_i$  point in different directions for the various surface elements as shown in **Figure 2.39**, but at each point they are normal to the surface and, by convention, always point outward. At the element labeled (1), the field lines are crossing the surface from the inside to the outside and  $\theta < 90^\circ$ ; hence, the flux  $\Delta \Phi_E = \mathbf{E} \cdot \Delta \mathbf{A}_1$  through this element is positive. For element (2), the field lines graze the surface (perpendicular to the vector  $\Delta \mathbf{A}_2$ ); thus,  $\theta = 90^\circ$  and the flux is zero. For elements such as (3), where the field lines are crossing the surface from outside to inside,  $180^\circ > \theta > 90^\circ$  and the flux is negative because  $\cos \theta$  is negative. The *net* flux through the surface is proportional to the net number of lines leaving the surface, where the net number means

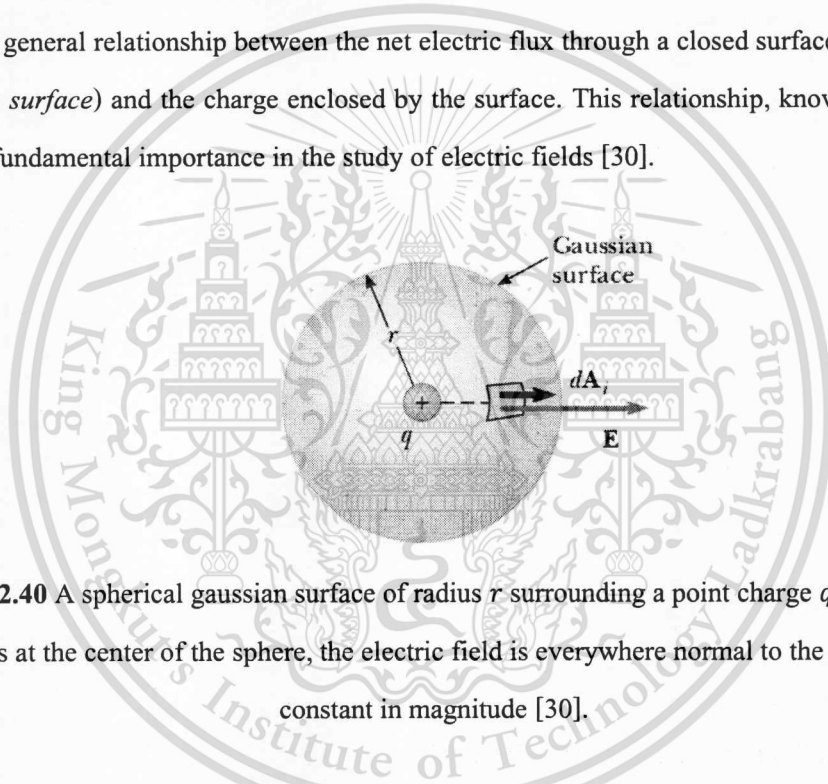
the number leaving the surface minus the number entering the surface. If more lines are leaving than entering, the net flux is positive. If more lines are entering than leaving, the net flux is negative. The symbol  $\oint$  is used to represent an integral over the closed surface, and the net flux  $\Phi_E$  through the closed surface is defined as

$$\Phi_E = \oint \mathbf{E} \cdot d\mathbf{A} = \oint E_n dA \quad (2.39)$$

Where  $E_n$  represents the component of the electric field normal to the surface.

### 2.5.2.2 Gauss's Law

A general relationship between the net electric flux through a closed surface (often called a *Gaussian surface*) and the charge enclosed by the surface. This relationship, known as *Gauss's law*, is of fundamental importance in the study of electric fields [30].



**Figure 2.40** A spherical gaussian surface of radius  $r$  surrounding a point charge  $q$ . When the charge is at the center of the sphere, the electric field is everywhere normal to the surface and constant in magnitude [30].

A positive point charge  $q$  is located at the center of a sphere of radius  $r$ , as shown in **Figure 2.40**. From **Equation 2.33**, the magnitude of the electric field everywhere on the surface of the sphere is  $E = k_e q / r^2$ . The field lines are directed radially outward and hence are perpendicular to the surface at every point on the surface. That is, at each surface point,  $\mathbf{E}$  is parallel to the vector  $\Delta \mathbf{A}_i$  representing a local element of area  $\Delta A_i$  surrounding the surface point. Therefore,

$$\mathbf{E} \cdot \Delta \mathbf{A}_i = E \Delta A_i \quad (2.40)$$

And from **Equation 2.39**, the net flux through the Gaussian surface is

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$$\Phi_E = \oint \mathbf{E} \cdot d\mathbf{A} = \oint E dA = E \oint dA \quad (2.41)$$

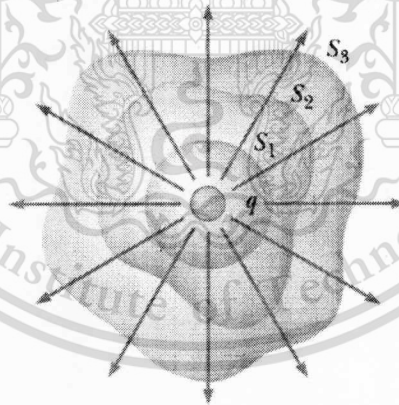
Where  $E$  is moved outside of the integral because, by symmetry,  $E$  is constant over the surface and given by  $E = k_e q / r^2$ . Furthermore, because the surface is spherical,  $\oint dA = A = 4\pi r^2$ . Hence, the net flux through the Gaussian surface is

$$\Phi_E = \frac{k_e q}{r^2} (4\pi r^2) = 4\pi k_e q \quad (2.42)$$

Where  $k_e = 1/4\pi\epsilon_0$ , thus this equation can be written as

$$\Phi_E = \frac{q}{\epsilon_0} \quad (2.43)$$

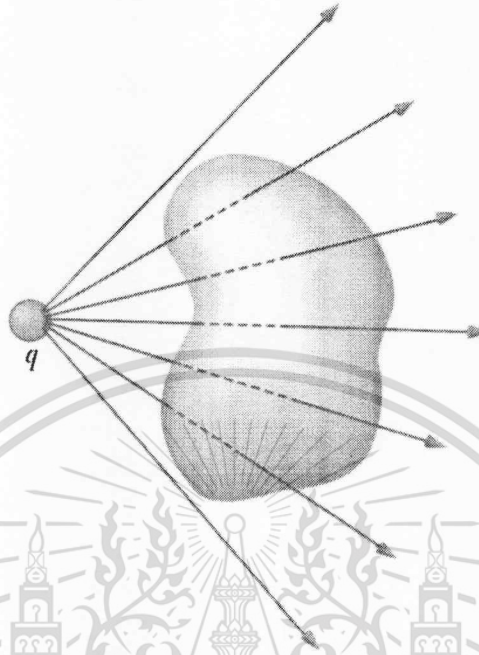
The net flux through the spherical surface is proportional to the charge inside, for **Equation 2.43**. The flux is independent of the radius  $r$  because the area of the spherical surface is proportional to  $r^2$ , whereas the electric field is proportional to  $1/r^2$ . Thus, in the product of area and electric field, the dependence on  $r$  cancels [30].



**Figure 2.41** Closed surfaces of various shapes surrounding a charge  $q$ . The net electric flux is the same through all surfaces [30].

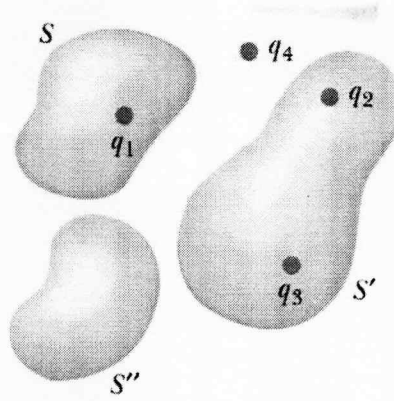
Several closed surfaces surrounding a charge  $q$  are shown in **Figure 2.41**. Surface  $S_1$  is spherical, but surfaces  $S_2$  and  $S_3$  are not. From **Equation 2.43**, the flux that passes through  $S_1$  has the value  $q/\epsilon_0$ . Flux is proportional to the number of electric field lines passing through a surface. The construction shown in **Figure 2.41** shows that the number of lines through  $S_1$  is equal to the number of lines through the nonspherical surfaces  $S_2$  and  $S_3$ . Therefore, **the net flux through any** This material is reserved for educational use only, not allowed for commercial use.

closed surface surrounding a point charge  $q$  is given by  $q/\epsilon_0$  and is independent of the shape of that surface [30].



**Figure 2.42** A point charge located *outside* a closed surface. The number of lines entering the surface equals the number leaving the surface [30].

A point charge located outside a closed surface of arbitrary shape is shown in **Figure 2.42**. Any electric field line that enters the surface leaves the surface at another point. The number of electric field lines entering the surface equals the number leaving the surface. Therefore, **the net electric flux through a closed surface that surrounds no charge is zero** [30].



**Figure 2.43** The net electric flux through any closed surface depends only on the charge *inside* that surface. The net flux through surface  $S$  is  $q_1/\epsilon_0$ , the net flux through surface  $S'$  is  $(q_2 + q_3)/\epsilon_0$ , and the net flux through surface  $S''$  is zero. Charge  $q_4$  does not contribute to the flux through any surface because it is outside all surfaces [30].

From the superposition principle, which states that **the electric field due to many charges is the vector sum of the electric fields produced by the individual charges**. Therefore, the flux through any closed surface is expressed as

$$\oint \mathbf{E} \cdot d\mathbf{A} = \oint (\mathbf{E}_1 + \mathbf{E}_2 + \dots) \cdot d\mathbf{A} \quad (2.44)$$

Where  $\mathbf{E}$  is the total electric field at any point on the surface produced by the vector addition of the electric fields at that point due to the individual charges. The system of charges is shown in **Figure 2.43**. The surface  $S$  surrounds only one charge,  $q_1$ ; hence, the net flux through  $S$  is  $q_1/\epsilon_0$ . The flux through  $S$  due to charges  $q_2$ ,  $q_3$ , and  $q_4$  outside it is zero because each electric field line that enters  $S$  at one point leaves it at another. The surface  $S'$  surrounds charges  $q_2$  and  $q_3$ ; hence, the net flux through it is  $(q_2 + q_3)/\epsilon_0$ . Finally, the net flux through surface  $S''$  is zero because there is no charge inside this surface. That is, *all* the electric field lines that enter  $S''$  at one point leave at another. Notice that charge  $q_4$  does not contribute to the net flux through any of the surfaces because it is outside all of the surfaces.

**Gauss's law**, describing the generalization, states that the net flux through *any* closed surface is

$$\Phi_E = \oint \mathbf{E} \cdot d\mathbf{A} = \frac{q_{in}}{\epsilon_0} \quad (2.45)$$



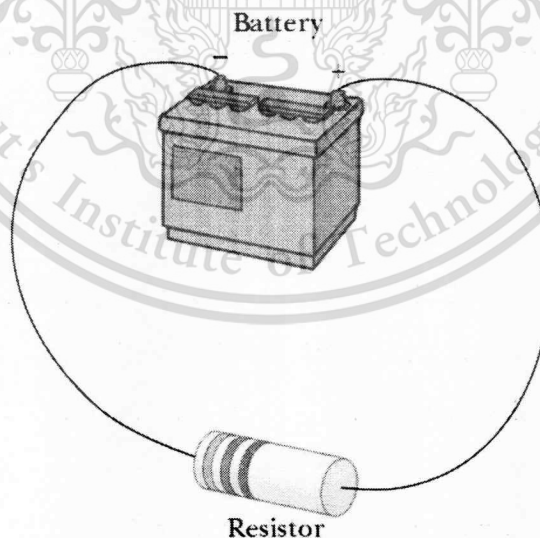
Where  $q_{\text{in}}$  represents the net charge inside the surface and  $\mathbf{E}$  represents the electric field at any point on the surface.

### 2.5.3 Direct Current Circuits

The analysis of more complicated circuits is simplified using two rules known as *Kirchhoff's rules*, which follow from the laws of conservation of energy and conservation of electric charge for isolated systems. Most of the circuits analysed are assumed to be in *steady state*, which means that currents in the circuit are constant in magnitude and direction. A current that is constant in direction is called a *direct current* (DC) [30].

#### 2.5.3.1 Electromotive Force

A battery is used as a source of energy for the circuit. Because the potential difference at the battery terminals is constant in a particular circuit, the current in the circuit is constant in magnitude and direction and is called **direct current**. A battery is called either a *source of electromotive force* or, more commonly, a *source of emf*. (The phrase *electromotive force* is an unfortunate historical term, describing not a force but rather a potential difference in volts.) **The emf  $\varepsilon$  of a battery is the maximum possible voltage that the battery can provide between its terminals** [30].



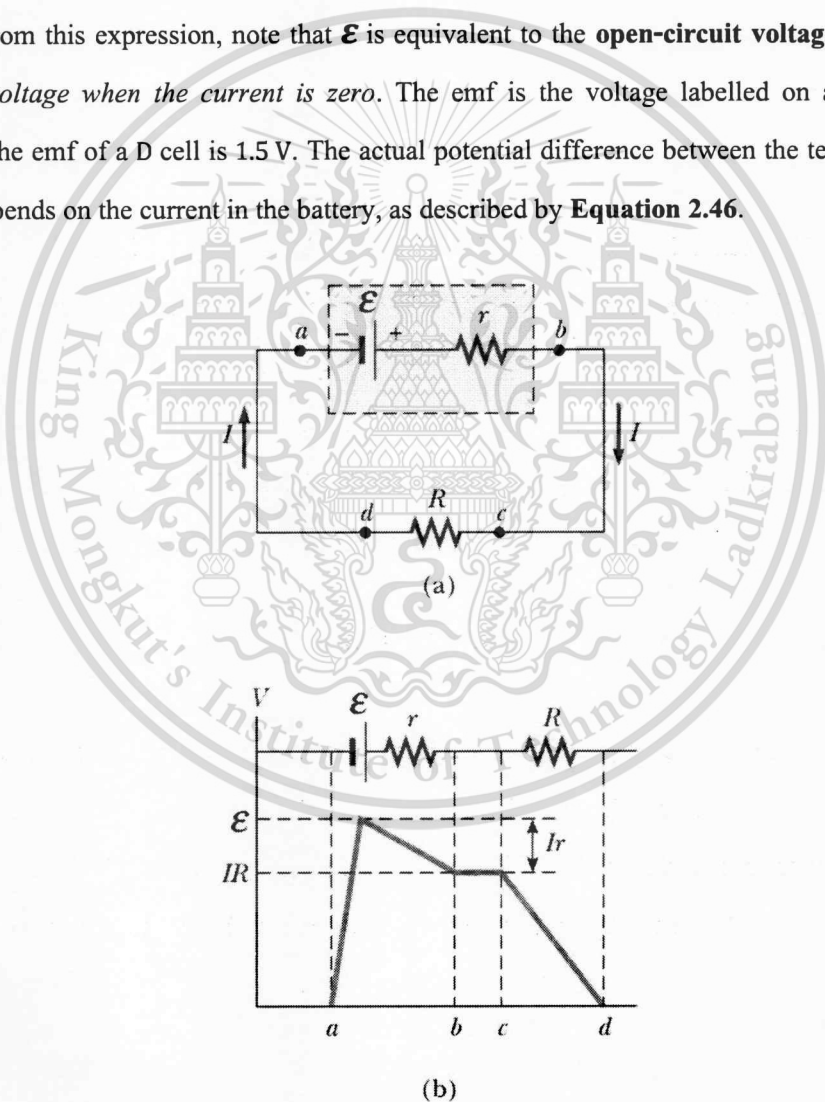
**Figure 2.44** A circuit consisting of a resistor connected to the terminals of a battery [30].

The circuit in **Figure 2.44** consists of a battery connected to a resistor (assume that the connecting wires have no resistance). The positive terminal of the battery is at a higher potential than the negative terminal because a real battery is made of matter, there is resistance to the flow. This material is reserved for educational use only, not allowed for commercial use.

of charge within the battery. This resistance is called **internal resistance**  $r$ . For an idealized battery with zero internal resistance, the potential difference across the battery (called its *terminal voltage*) equals its emf. However, for a real battery, the terminal voltage is *not* equal to the emf for a battery in a circuit in which there is a current. The battery of **Figure 2.44** is represented by the dashed rectangle containing an ideal as shown in **Figure 2.45a**, emf  $\mathcal{E}$  in series with an internal resistance  $r$ . Thus, the terminal voltage of the battery  $\Delta V = V_b - V_a$  is

$$\Delta V = \mathcal{E} - I_r \tag{2.46}$$

From this expression, note that  $\mathcal{E}$  is equivalent to the **open-circuit voltage**—that is, the *terminal voltage when the current is zero*. The emf is the voltage labelled on a battery—for example, the emf of a D cell is 1.5 V. The actual potential difference between the terminals of the battery depends on the current in the battery, as described by **Equation 2.46**.



**Figure 2.45** (a) Circuit diagram of a source of emf  $\mathcal{E}$  (in this case, a battery), of internal resistance  $r$ , connected to an external resistor of resistance  $R$ . (b) Graphical representation showing how the electric potential changes as the circuit in part (a) is traversed clockwise [30].

A graphical representation of the changes in electric potential as the circuit is traversed in the clockwise direction is shown in **Figure 2.45b**. The terminal voltage  $\Delta V$  must equal the potential difference across the external resistance  $R$ , often called the **load resistance**. The load resistor might be a simple resistive circuit element, as in **Figure 2.44**, or it could be the resistance of some electrical device (such as a toaster, an electric heater, or a lightbulb) connected to the battery (or, in the case of household devices, to the wall outlet). The resistor represents a *load* on the battery because the battery must supply energy to operate the device. The potential difference across the load resistance is  $\Delta V = IR$ . Combining this expression with **Equation 2.46**, thus

$$\mathcal{E} = IR + Ir \quad (2.47)$$

Solving for the current gives

$$I = \frac{\mathcal{E}}{R+r} \quad (2.48)$$

This equation shows that the current in this simple circuit depends on both the load resistance  $R$  external to the battery and the internal resistance  $r$ . If  $R$  is much greater than  $r$ , as it is in many real-world circuits, we can neglect  $r$ .

multiply **Equation 2.47** by the current  $I$ , thus

$$I\mathcal{E} = I^2R + I^2r \quad (2.49)$$

This equation indicates that, because power  $\mathcal{P} = I\Delta V$ , the total power output  $I\mathcal{E}$  of the battery is delivered to the external load resistance in the amount  $I^2R$  and to the internal resistance in the amount  $I^2r$ .

#### 2.5.4 Magnetic Fields

In 1296 a Frenchman named Pierre de Maricourt found that the directions of a needle near a spherical natural magnet formed lines that encircled the sphere and passed through two points diametrically opposite each other, which he called the *poles* of the magnet. Subsequent experiments showed that every magnet, regardless of its shape, has two poles, called *north* (N) and *south* (S) poles, that exert forces on other magnetic poles similar to the way that electric charges exert forces on one another. That is, like poles (N-N or S-S) repel each other, and opposite poles (N-S) attract each other [30].

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The poles received their names because of the way a magnet, such as that in a compass, behaves in the presence of the Earth's magnetic field. If a bar magnet is suspended from its midpoint and can swing freely in a horizontal plane, it will rotate until its north pole point to the Earth's geographic North Pole and its south pole points to the Earth's geographic South Pole [30].

In 1600 William Gilbert (1540-1603) extended de Maricourt's experiments to a variety of materials. Using the fact that a compass needle orients in preferred directions, he suggested that the Earth itself is a large permanent magnet. In 1750 experimenters used a torsion balance to show that magnetic poles exert attractive or repulsive forces on each other and that these forces vary as the inverse square of the distance between interacting poles. Although the force between two magnetic poles is otherwise similar to the force between two electric charges, electric charges can be isolated (witness the electron and proton) whereas **a single magnetic pole has never been isolated. That is, magnetic poles are always found in pairs.** All attempts thus far to detect an isolated magnetic pole have been unsuccessful. No matter how many times a permanent magnet is cut in two, each piece always has a north and a south pole [30].

The relationship between magnetism and electricity was discovered in 1819 when, during a lecture demonstration, the Danish scientist Hans Christian Oersted found that an electric current in a wire deflected a nearby compass needle. In the 1820s, further connections between electricity and magnetism were demonstrated independently by Faraday and Joseph Henry (1797-1878). They showed that an electric current can be produced in a circuit either by moving a magnet near the circuit or by changing the current in a nearby circuit. These observations demonstrate that a changing magnetic field creates an electric field. Year later, theoretical work by Maxwell showed that the reverse is also true: a changing electric field creates a magnetic field [30].

#### 2.5.4.1 Magnetic Fields and Forces

The SI unit of magnetic field is the newton per coulomb-meter per second, which is called the **tesla** (T):

$$1 \text{ T} = 1 \frac{\text{N}}{\text{C}\cdot\text{m/s}} \quad (2.50)$$

Because a coulomb per second is defined to be an ampere, thus

$$1 \text{ T} = 1 \frac{\text{N}}{\text{A}\cdot\text{m}} \quad (2.51)$$

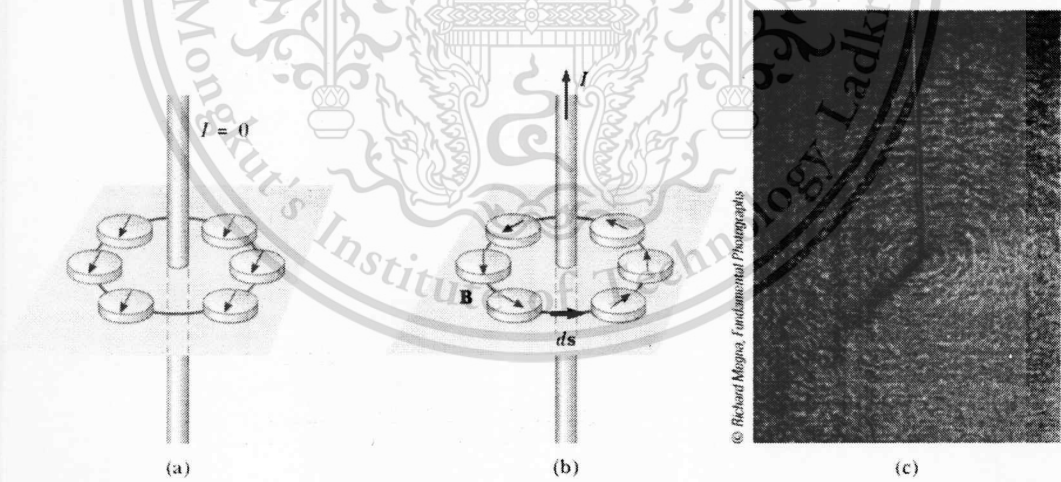
A non-SI magnetic-field unit is common use, called the *gauss* (G), is related to the tesla through the conversion  $1\text{ T} = 10^4\text{ G}$ . **Table 2.7** shows some typical values of magnetic fields.

**Table 2.7** Some approximate magnetic field magnitudes [30].

| Source of Field                            | Field Magnitude (T)  |
|--------------------------------------------|----------------------|
| Strong superconducting laboratory magnet   | 30                   |
| Strong conventional laboratory magnet      | 2                    |
| Medical MRI unit                           | 1.5                  |
| Bar magnet                                 | $10^{-2}$            |
| Surface of the Sun                         | $10^{-2}$            |
| Surface of the Earth                       | $0.5 \times 10^{-4}$ |
| Inside human brain (due to nerve impulses) | $10^{-13}$           |

2.5.4.2 Ampere’s Law

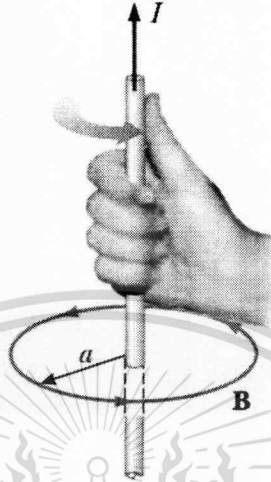
Oersted’s 1819 discovery about deflected compass needles demonstrates that a current-carrying conductor produces a magnetic field [30].



**Figure 2.46** (a) When no current is present in the wire, all compass needles point in the same direction (toward the Earth’s north pole). (b) When the wire carries a strong current, the compass needles deflect in a direction tangent to the circle, which is the direction of the magnetic field created by the current. (c) Circular magnetic field lines surrounding a current-carrying conductor, displayed with iron filings [30].



The lines of  $\mathbf{B}$  form circles around the wire. The magnitude of  $\mathbf{B}$  is the same everywhere on a circular path, centered on the wire and lying in a plane perpendicular to the wire, where  $B$  is proportional to the current and inversely proportional to the distance from the wire [30].



**Figure 2.47** The right-hand rule for determining the direction of the magnetic field surrounding a long, straight wire carrying a current. Note that the magnetic field lines form circle around the wire [30].

The product  $\mathbf{B} \cdot d\mathbf{s}$  for a small length element  $d\mathbf{s}$  on the circular path is defined by the compass needles, and the sum of the products for all elements over the closed circular path. Along this path, the vectors  $d\mathbf{s}$  and  $\mathbf{B}$  are parallel at each point (see **Figure 2.46b**), so  $\mathbf{B} \cdot d\mathbf{s} = B ds$ . Furthermore, the magnitude of  $\mathbf{B}$  is constant on this circle. Therefore, the sum of the products  $B ds$  over the closed path, which is equivalent to the line integral of  $\mathbf{B} \cdot d\mathbf{s}$ , is

$$\oint \mathbf{B} \cdot d\mathbf{s} = B \oint ds = \frac{\mu_0 I}{2\pi r} (2\pi r) = \mu_0 I \quad (2.52)$$

Where  $\oint ds = 2\pi r$  is the circumference of the circular path. Although this result was calculated for the special case of a circular path surrounding a wire, it holds for a closed path of any shape (an *amperian loop*) surrounding a current that exists in an unbroken circuit. The general case, known as **Ampère's law**, can be stated as follows:

The line integral of  $\mathbf{B} \cdot d\mathbf{s}$  around any closed path equals  $\mu_0 I$ , where  $I$  is the total steady current passing through any surface bounded by the closed path.

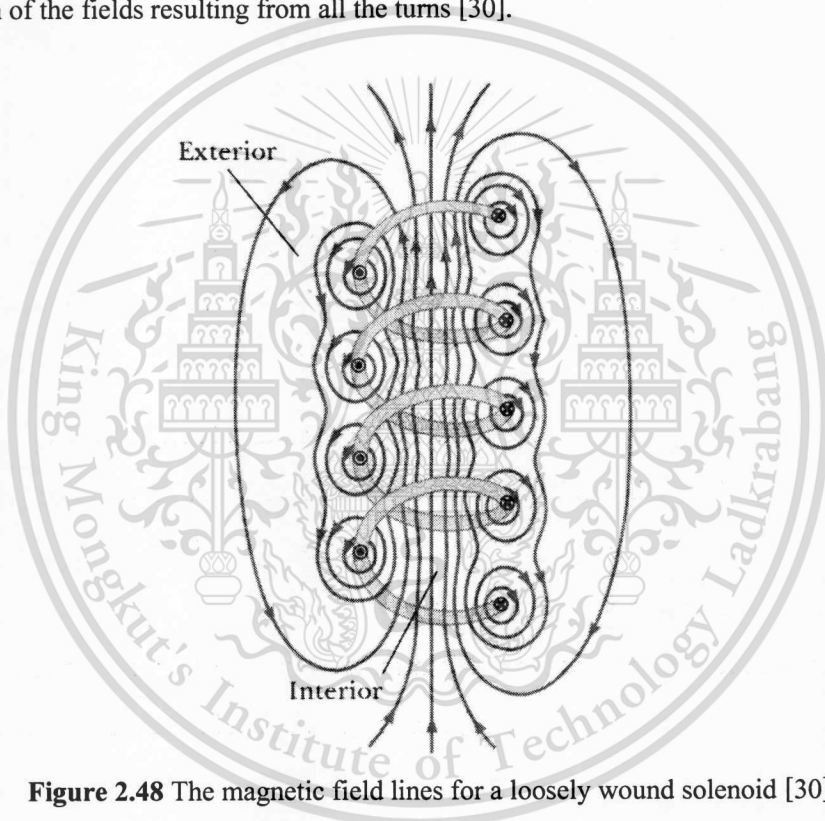
$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I \quad (2.53)$$



Ampère's law describes the creation of magnetic fields by all continuous current configurations. The Ampère's law is similar to that of Gauss's law in calculating electric fields for highly symmetric charge distributions.

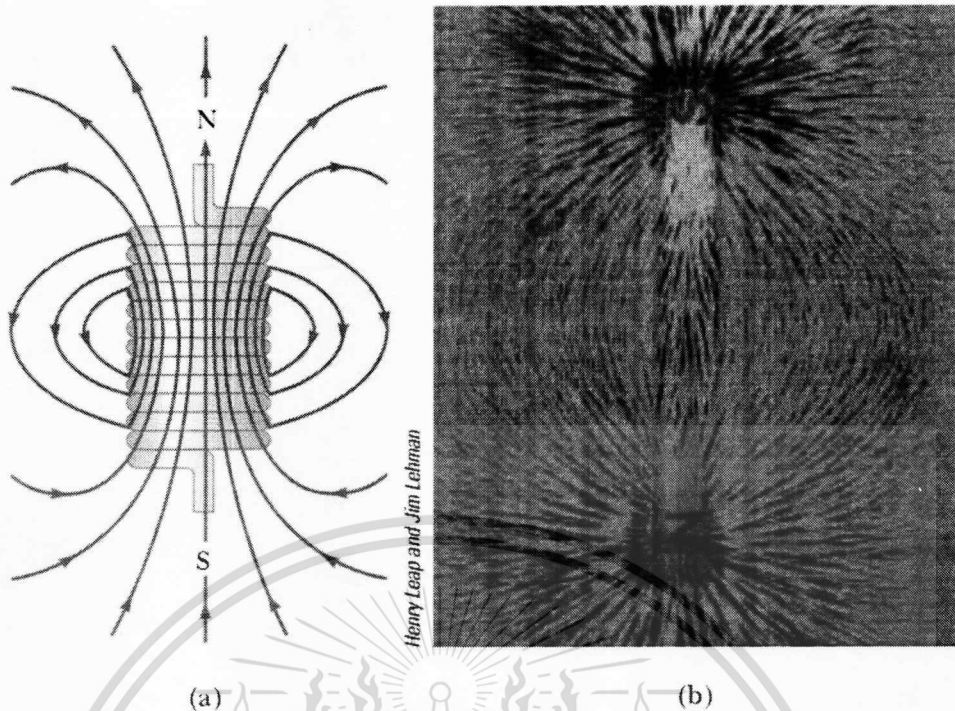
#### 2.5.4.3 The Magnetic Field of a Solenoid

A solenoid is a long wire wound in the form of a helix. With this configuration, a reasonably uniform magnetic field can be produced in the space surround by the turns of wire, called the interior of the solenoid—when the solenoid carries a current. When the turns are closely spaced, each can be approximated as a circular loop, and the net magnetic field is the vector sum of the fields resulting from all the turns [30].



**Figure 2.48** The magnetic field lines for a loosely wound solenoid [30].

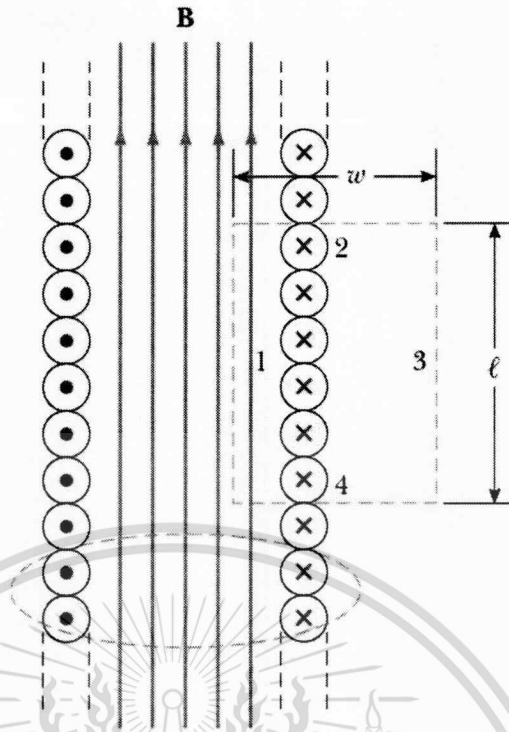
The magnetic field lines surrounding a loosely wound solenoid is shown in **Figure 2.48**. Note that the field lines in the interior are nearly parallel to one another, are uniformly distributed, and are close together, indicating that the field in this space is strong and almost uniform [30].



**Figure 2.49** (a) Magnetic field lines for a tightly wound solenoid of finite length, carrying a steady current. The field in the interior space is strong and nearly uniform. Note that the field lines resemble those of a bar magnet, meaning that the solenoid effectively has north and south poles. (b) The magnetic field pattern of a bar magnet, displayed with small iron filings on a sheet of paper [30].

If the turns are tightly wound and the solenoid has finite length, the magnetic field lines will look like the lines, shown in **Figure 2.49a**. This field line distribution is similar to that surrounding a bar magnet (see **Figure 2.49b**). Hence, one end of the solenoid behaves like the north pole of a magnet, and the opposite end behaves like the south pole. As the length of the solenoid increases, the interior field becomes more uniform and the exterior field becomes weaker. An *ideal solenoid* is approached when the turns are tightly wound and the length is much greater than the radius of the turns. A longitudinal cross section of part of such a solenoid carrying a current  $I$  is shown in **Figure 2.50**. In this case, the external field is close to zero, and the interior field is uniform over a great volume [30].





**Figure 2.50** Cross-sectional view of an ideal solenoid, where the interior magnetic field is uniform and the exterior field is close to zero. Ampère's law applied to the circular path near the bottom whose plane is perpendicular to the page can be used to show that there is a weak field outside the solenoid. Ampère's law applied to the rectangular dashed path in the plane of the page can be used to calculate the magnitude of the interior field [30].

For an ideal solenoid, this is the only field external to the solenoid. This field in **Figure 2.50** can be eliminated by adding a second layer of turns of wire outside the first layer, with the current carried along the axis of the solenoid in the opposite direction compared to the first layer. Then the net current along the axis is zero [30].

The Ampère's law is used to obtain a quantitative expression for the interior magnetic field in an ideal solenoid. For the ideal solenoid,  $\mathbf{B}$  in the interior space is uniform and parallel to the axis, and the magnetic field lines in the exterior space form circles around the solenoid. The planes of these circles are perpendicular to the page. The Ampère's law that was applied for the rectangular path of length  $l$  and width  $w$  is shown in **Figure 2.50**. The contribution along side 3 is zero because the magnetic field lines are perpendicular to the path in this region. The contributions from sides 2 and 4 are both zero, again because  $\mathbf{B}$  is perpendicular to  $d\mathbf{s}$  along these paths, both inside and outside the solenoid. Side 1 gives a contribution to the integral because



along this path  $\mathbf{B}$  is uniform and parallel to  $d\mathbf{s}$ . The integral over the closed rectangular path is therefore

$$\oint \mathbf{B} \cdot d\mathbf{s} = \int_{\text{path } 1} \mathbf{B} \cdot d\mathbf{s} = B \int_{\text{path } 1} ds = Bl \quad (2.54)$$

The right side of Ampère's law involves the total current  $I$  through the area bounded by the path of integration. In this case, the total current through the rectangular path equals the current through each turn multiplied by the number of turns. If  $N$  is the number of turns in the length  $l$ , the total current through the rectangle is  $NI$ . Therefore, applied to this path gives

$$\oint \mathbf{B} \cdot d\mathbf{s} = Bl = \mu_0 NI \quad (2.55)$$

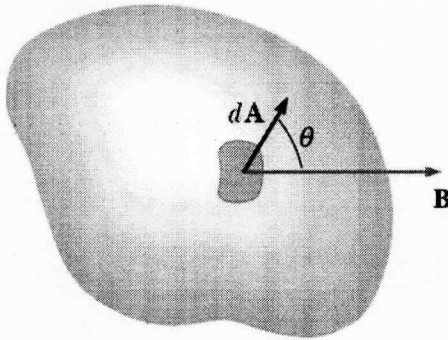
$$B = \mu_0 \frac{N}{l} I = \mu_0 n I \quad (2.56)$$

Where  $n = N/l$  is the number of turns per unit length.

#### 2.5.4.4 Magnetic Flux

The flux associated with a magnetic field is defined in a manner similar to that used to defined electric flux (see **Equation 2.38**). An element of area  $dA$  on an arbitrarily shaped surface, is shown in **Figure 2.51**. If the magnetic field at this element is  $\mathbf{B}$ , the magnetic flux through the element is  $\mathbf{B} \cdot d\mathbf{A}$ , where  $d\mathbf{A}$  is a vector that is perpendicular to the surface and has a magnitude equal to the area  $dA$ . Therefore, the total magnetic flux  $\Phi_B$  through the surface is

$$\Phi_B = \oint \mathbf{B} \cdot d\mathbf{A} \quad (2.57)$$



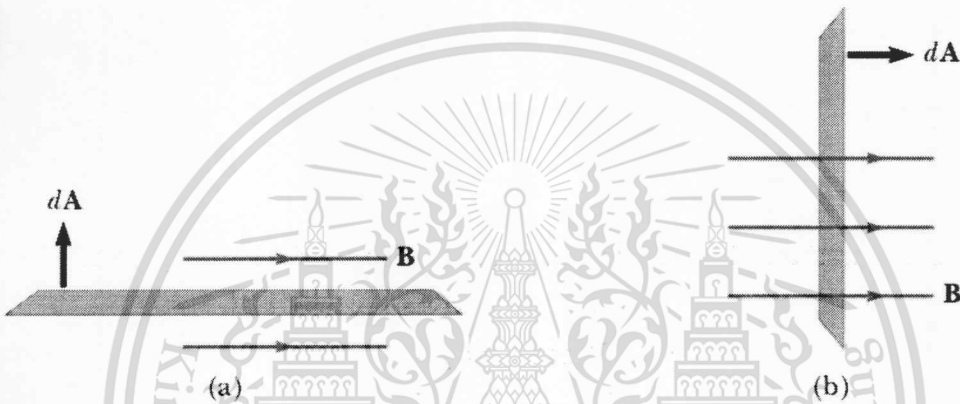
**Figure 2.51** The magnetic flux through an area element  $dA$  is  $\mathbf{B} \cdot d\mathbf{A} = B dA \cos \theta$ , where  $d\mathbf{A}$  is a vector perpendicular to the surface [30].

The magnetic flux through the plane that has an angle  $\theta$  with  $d\mathbf{A}$  is expressed as follows:

$$\Phi_B = BA \cos \theta \quad (2.58)$$

If the magnetic field is parallel to the plane, as in **Figure 2.52a**, then  $\theta = 90^\circ$  and the flux through the plane is zero. If the field is perpendicular to the plane, as in **Figure 2.52b**, then  $\theta = 0$  and the flux through the plane is  $BA$  (the maximum value).

The unit of magnetic flux is  $\text{T} \cdot \text{m}^2$ , which is defined as a *weber* (Wb);  $1 \text{ Wb} = 1 \text{ T} \cdot \text{m}^2$ .



**Figure 2.52** Magnetic flux through a plane lying in a magnetic field. (a) The flux through the plane is zero when the magnetic field is parallel to the plane surface. (b) The flux through the plane is a maximum when the magnetic field is perpendicular to the plane [30].

### 2.5.5 Faraday's Law

Experiments conducted by Michael Faraday in England in 1831 and independently by Joseph Henry in the United States in the same year showed that an emf can be induced in a circuit by a changing magnetic field. The results of these experiments led to a very basic and important law of electromagnetism known as *Faraday's law of induction*. An emf (and therefore a current as well) can be induced in various processes that involve a change in a magnetic flux [30].

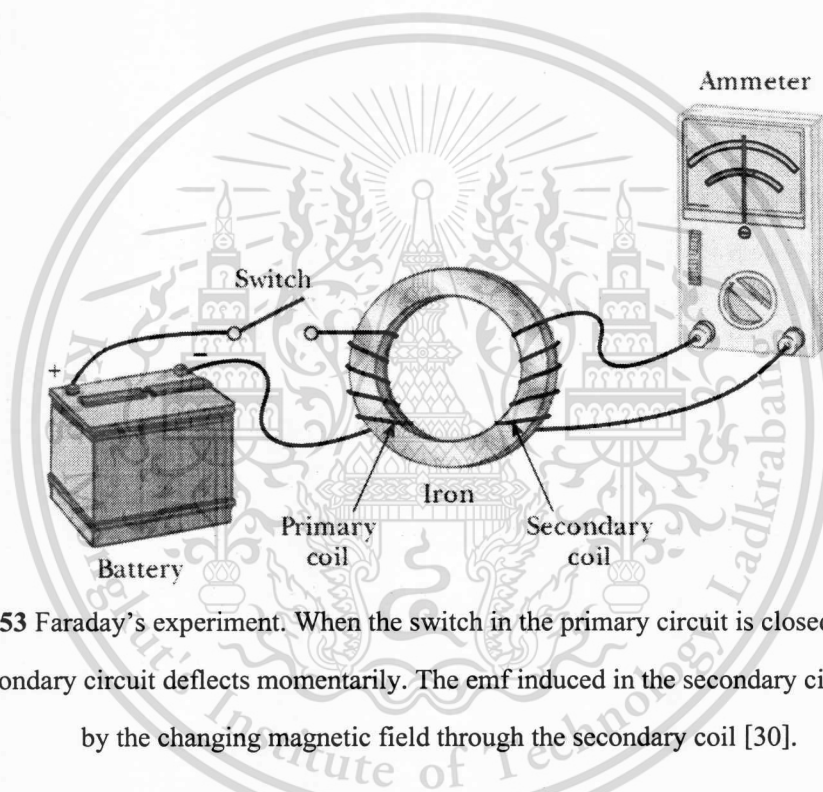
These laws can be summarized in a set of four equations called *Maxwell's equations*. Together with the *Lorentz force law*, they represent a complete theory for describing the interaction of charged objects [30].

#### 2.5.5.1 Faraday's Law of induction

An experiment conducted by Faraday is illustrated in **Figure 2.53**. A primary coil is connected to a switch and a battery. The coil is wrapped around an iron ring, and a current in the

coil produces a magnetic field when the switch is closed. A secondary coil also is wrapped around the ring and is connected to a sensitive ammeter. No battery is present in the secondary circuit, and the secondary coil is not electrically connected to the primary coil. Any current detected in the secondary circuit must be induced by some external agent [30].

Initially, there is no current in the secondary circuit. However, when the switch in the primary circuit is closed, the galvanometer needle deflects in one direction and then returns to zero. And when the switch in the primary circuit is opened, the needle deflects in the opposite direction and again returns to zero.



**Figure 2.53** Faraday's experiment. When the switch in the primary circuit is closed, the ammeter in the secondary circuit deflects momentarily. The emf induced in the secondary circuit is caused by the changing magnetic field through the secondary coil [30].

Finally, when there is either a steady current or no current in the primary circuit the galvanometer reads zero. These results can be explained by the current in the primary circuit produces a magnetic field that penetrates the secondary circuit when the switch is closed. Furthermore, the magnetic field produced by the current in the primary circuit changes from zero to some value over some finite time, and this changing field induces a current in the secondary circuit.

As a result of these observations, Faraday concluded that **an electric current can be induced in a circuit (the secondary circuit in our setup) by a changing magnetic field**. The induced current exists for only a short time while the magnetic field through the secondary coil is

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changing. Once the magnetic field reaches a steady value, the current in the secondary coil disappears. In effect, the secondary circuit, behaved as a source of emf were connected to it for a short time. It is customary to say that **an induced emf is produced in the secondary circuit by the changing magnetic field** [30].

The emf induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit.

This statement, known as **Faraday's law of induction**, can be written as follow:

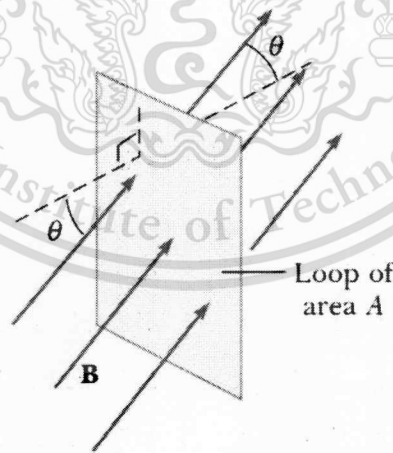
$$\mathcal{E} = -\frac{d\Phi_B}{dt} \quad (2.59)$$

Where  $\Phi_B = \int \mathbf{B} \cdot d\mathbf{A}$  is the magnetic flux through the circuit.

If the circuit is a coil consisting of  $N$  loops all of the same area and if  $\Phi_B$  is the magnetic flux through one loop, an emf is induced in every loop. The loops are in series, so their emfs add. Thus, the total induced emf in the coil is given by the following expression:

$$\mathcal{E} = -N \frac{d\Phi_B}{dt} \quad (2.60)$$

The negative sign in **Equation 2.61** and **2.62** is of important physical significance.



**Figure 2.54** A conducting loop that encloses an area  $A$  in the presence of a uniform magnetic field  $\mathbf{B}$ . The angle between  $\mathbf{B}$  and the normal to the loop is  $\theta$  [30].

For example, if a loop enclosing an area  $A$  lies in a uniform magnetic field  $\mathbf{B}$ , as in **Figure 2.54**, the magnetic flux through the loop is equal to  $BA \cos \theta$ . Hence, the induced emf can be expressed as

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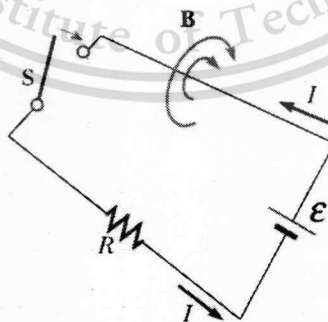
$$\mathcal{E} = -\frac{d}{dt}(BA \cos \theta) \quad (2.61)$$

### 2.5.6 Inductance

Self-induction is an effect that occurs when the current is varying in a circuit and produces an induced emf opposing the emf, that initially set up the time-varying current. So, self-induction is the basis of the inductor, an electrical circuit element [30].

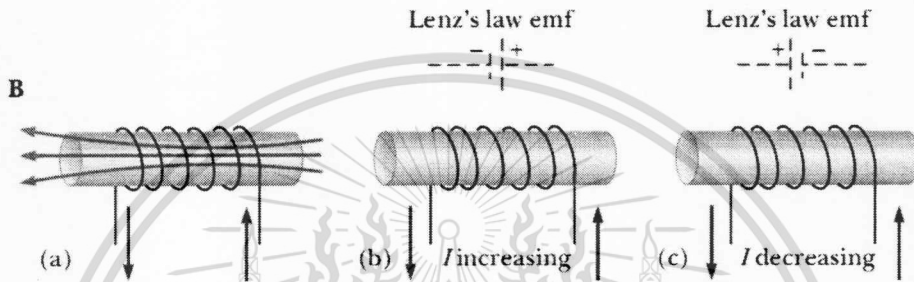
#### 2.5.6.1 Self-Inductance

A circuit consisting of a switch, a resistor, and a source of emf, are shown in **Figure 2.55**. When the switch is thrown to the closed position, the current does not immediately jump from zero to its maximum value  $\mathcal{E}/R$ . Faraday's law of electromagnetic induction (**Equation 2.59**) can be used to describe this effect as follows: as the current increases with time, the magnetic flux through the circuit loop due to this current also increases with time. This increasing flux creates an induced emf in the circuit. The direction of the induced emf is such that it would cause an induced current in the loop (if the loop did not already carry a current), which would establish a magnetic field opposing the change in the original magnetic field. Thus, the direction of the induced emf is opposite the direction of the emf of the battery. This results in a gradual rather than instantaneous increase in the current to its final equilibrium value. The direction of the induced emf is negative sign, so it also called a *back emf*, similar to that in a motor. This effect is called **self-induction** because the changing flux through the circuit and the resultant induced emf arise from the circuit itself. The emf  $\mathcal{E}_L$  set up in this case is called a **self-induced emf** [30].



**Figure 2.55** After the switch is closed, the current produces a magnetic flux through the area enclosed by the loop. As the current increases toward its equilibrium value, this magnetic flux changes in time and induces an emf in the loop [30].

A coil wound on a cylindrical core is shown in **Figure 2.56**. When the current is in the direction shown, a magnetic field directed from right to left is set up inside the coil, as seen in **Figure 2.56a**. As the current changes with time, the magnetic flux through the coil also changes and induces an emf in the coil. From Lenz's law, the polarity of this induced emf must be such that it opposes the change in the magnetic field from the current. If the current is increasing, the polarity of the induced emf is as pictured in **Figure 2.56b**, and if the current is decreasing, the polarity of the induced emf is as shown in **Figure 2.56c**.



**Figure 2.56** (a) A current in the coil produces a magnetic field directed to the left. (b) If the current increases, the increasing magnetic flux creates an induced emf in the coil having the polarity shown by the dashed battery. (c) The polarity of the induced emf reverses if the current decreases [30].

The magnetic flux is proportional to the magnetic field due to the current, which in turn is proportional to the current in the circuit. Therefore, **a self-induced emf is always proportional to the time rate of change of the current**, and is defined as follows:

$$\mathcal{E}_L = -L \frac{dI}{dt} \quad (2.62)$$

Where  $L$  is a proportionality constant, called the inductance of the coil, that depends on the geometry of the coil and other physical characteristics. By combining this expression with Faraday's law,  $\mathcal{E}_L = -N d\Phi_B/dt$ , the inductance of a closely spaced coil (a toroid or an ideal solenoid) carries a current  $I$  and contains  $N$  turns, which can be expressed as follows:

$$L = \frac{N\Phi_B}{I} \quad (2.63)$$

Where it is assumed that the same magnetic flux passes through each turn.

From **Equation 2.62**, the inductance can be written as the following ratio:

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$$L = -\frac{\mathcal{E}_L}{di/dt} \quad (2.64)$$

The SI unit of inductance is the **henry (H)** (see from **Equation 2.64**) is 1 volt-second per ampere:

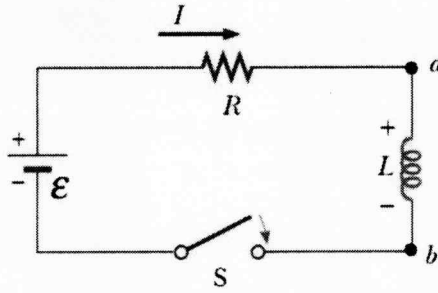
$$1 \text{ H} = 1 \frac{\text{V}\cdot\text{s}}{\text{A}} \quad (2.65)$$

### 2.5.6.2 R-L Circuits

The self-inductance of the coil prevents the current in the circuit from increasing or decreasing instantaneously. A circuit element that has a large self-inductance is called an inductor. The self-inductance of the remainder of a circuit was assumed to be negligible compared with that of the inductor. However, even a circuit without a coil still has some self-inductance that can affect the behavior of the circuit [30].

The inductance of the inductor results in a back emf. In other words, **an inductor in a circuit opposes changes in the current in that circuit**. The inductor attempts to keep the current the same as it was before the change occurred. If the battery voltage in the circuit is increased so that the current rises, the inductor opposes this change, and the rise is not instantaneous. If the battery voltage is decreased, the presence of the inductor results in a slow drop in the current rather than an immediate drop. Thus, the inductor causes the circuit to be “sluggish” as it reacts to changes in the voltage [30].

The circuit, which contains a battery of negligible internal resistance, is shown in **Figure 2.57**. This is an **RL circuit** because the elements connected to the battery are a resistor and an inductor. Suppose that the switch S is open for  $t < 0$  and then closed at  $t = 0$ . The current in the circuit begins to increase, and a back emf (**Equation 2.62**) that opposes the increasing current is induced in the inductor. As the current is increasing,  $di/dt$  in **Equation 2.62** is positive. Thus,  $\mathcal{E}_L$  is negative. This negative value reflects the decrease in electric potential that occurs in going from  $a$  to  $b$  across the inductor, as indicated by the positive and negative signs in **Figure 2.57**.



**Figure 2.57** A series  $RL$  circuit. As the current increases toward its maximum value, an emf that opposes the increasing current is induced in the inductor [30].

Kirchhoff's loop rule can be applied to this circuit, traversing the circuit in the clockwise direction:

$$\mathcal{E} - IR - L \frac{dI}{dt} = 0 \quad (2.66)$$

Where  $IR$  is the voltage drop across the resistor.

A mathematical solution of **Equation 2.66** represents the current in the circuit as a function of time. To find the solution, letting  $x = (\mathcal{E}/R) - I$ , so that  $dx = -dI$ . With these substitutions, the **Equation 2.66** can be written as follows:

$$x + \frac{L}{R} \frac{dx}{dt} = 0 \quad (2.67)$$

$$\frac{dx}{x} = -\frac{R}{L} dt \quad (2.68)$$

Integrating **Equation 2.68** in order to get the following equations:

$$\int_{x_0}^x \frac{dx}{x} = -\frac{R}{L} \int_0^t dt \quad (2.69)$$

$$\ln \frac{x}{x_0} = -\frac{R}{L} t \quad (2.70)$$

Where  $x_0$  is the value of  $x$  at time  $t = 0$ . Then, apply the antilogarithm to obtain

$$x = x_0 e^{-Rt/L} \quad (2.71)$$

Where  $I = 0$  at  $t = 0$ , from the definition of  $x$  that  $x_0 = \mathcal{E}/R$ . Thus, the **Equation 2.71** is equivalent to

$$\frac{\mathcal{E}}{R} - I = \frac{\mathcal{E}}{R} e^{-Rt/L} \quad (2.72)$$

$$I = \frac{\mathcal{E}}{R} (1 - e^{-Rt/L}) \quad (2.73)$$

This expression shows behavior of the current in an inductor. The current does not increase instantly to its final equilibrium value when the switch is closed but instead increases according to an exponential function.

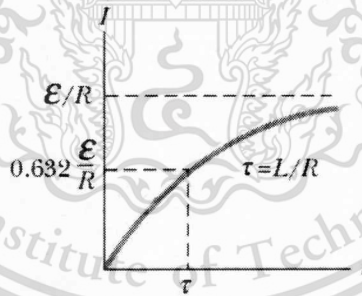
**Equation 2.71** can be written as follows:

$$I = \frac{\mathcal{E}}{R} (1 - e^{-t/\tau}) \quad (2.74)$$

Where the constant  $\tau$  is the **time constant** of the  $RL$  circuit:

$$\tau = \frac{L}{R} \quad (2.75)$$

Physically,  $\tau$  is the time interval required for the current in the circuit to reach  $(1 - e^{-1}) = 0.632 = 63.2\%$  of its final value  $\mathcal{E}/R$ . The time constant is a useful parameter for comparing the time responses of various circuits.



**Figure 2.58** Plot of the current versus time for the  $RL$  circuit shown in **Figure 2.71**. The switch is open for  $t < 0$  and then closed at  $t = 0$ , and the current increases toward its maximum value  $\mathcal{E}/R$ . The time constant  $\tau$  is the time interval required for  $I$  to reach 63.2% of its maximum value [30].

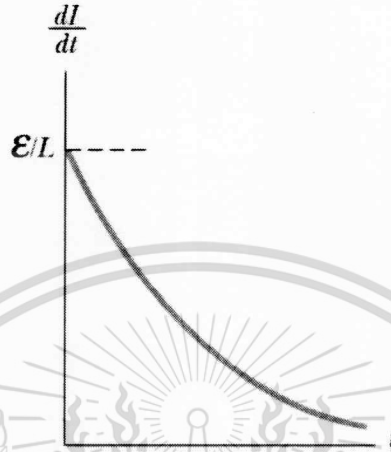
A graph of the current versus time in the  $RL$  circuit is shown in **Figure 2.58**. Note that the equilibrium value of the current, which occurs as  $t$  approaches infinity, is  $\mathcal{E}/R$ . This can be explained by setting  $dI/dt$  equal to zero in **Equation 2.66** and solving for the current  $I$  (At equilibrium, the change in the current is zero).

The time rate of change of the current can be derived from **Equation 2.74**, and is expressed as follows:



$$\frac{dI}{dt} = \frac{\mathcal{E}}{L} e^{-t/\tau} \quad (2.76)$$

From this result, the time rate of change of the current is a maximum (equal to  $\mathcal{E}/L$ ) at  $t = 0$ , and falls off exponentially to zero as  $t$  approaches infinity (**Figure 2.59**).



**Figure 2.59** Plot of  $dI/dt$  versus time for the  $RL$  circuit shown in **Figure 2.57**. The time rate of change of current is a maximum at  $t = 0$ , which is the instant at which the switch is closed. The rate decreases exponentially with time as  $I$  increases toward its maximum value [30].

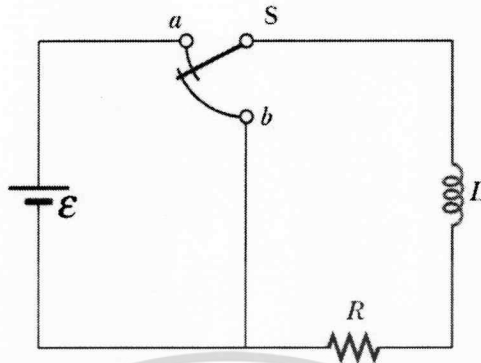
The  $RL$  circuit is shown in **Figure 2.60**. The curved lines on the switch  $S$  represent a switch that is connected either to  $a$  or  $b$  all times. Suppose that the switch has been set at position  $a$  long enough to allow the current to reach its equilibrium value  $\mathcal{E}/R$ . In this situation, the circuit is described by the outer loop in **Figure 2.60**. If the switch is thrown from  $a$  to  $b$ , the circuit is now described by the right hand loop in **Figure 2.60**. By applying Kirchhoff's loop rule to the right-hand loop at the time the switch is thrown from  $a$  to  $b$ , **Equation 2.77** is obtained as follows:

$$IR + L \frac{dI}{dt} = 0 \quad (2.77)$$

The solution of this differential equation is

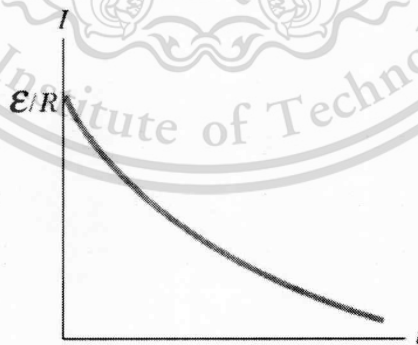
$$I = \frac{\mathcal{E}}{L} e^{-t/\tau} = I_0 e^{-t/\tau} \quad (2.78)$$

Where  $\mathcal{E}$  is the emf of the battery and  $I_0 = \mathcal{E}/R$  is the current when the switch is thrown to  $b$ .



**Figure 2.60** An  $RL$  circuit. When the switch  $S$  is in position  $a$ , the battery is in the circuit. When the switch is thrown to position  $b$ , the battery is no longer part of the circuit. The switch is designed so that it is never open, which would cause the current to stop [30].

The circuit that does not have an inductor, the current would immediately decrease to zero when the battery is removed. When the inductor is present, it opposes the decrease in the current and causes the current to decrease exponentially. A graph of the current in the circuit versus time (**Figure 2.61**) shows that the current is continuously decreasing with time. Note that the slope  $dI/dt$  is always negative and has its maximum value at  $t = 0$ . The negative slope signifies that  $\mathcal{E}_L = -L(dI/dt)$  is positive [30].



**Figure 2.61** Current versus time for the right-hand loop of the circuit shown in **Figure 2.60**.

For  $t < 0$ , the switch  $S$  is at position  $a$ . At  $t = 0$ , the switch is thrown to position  $b$ , and the current has its maximum value  $\mathcal{E}/R$  [30].

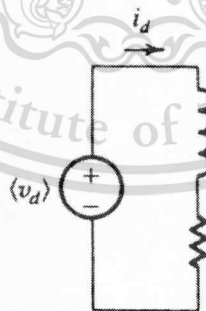
## CHAPTER 3

# MATERIALS AND METHODS

In this chapter, a circuit design consisting of control unit and magnetic fixture is described. Next, we show the process of design, writing, testing and debugging of the microcontroller are given. Determination of the performance of magnetizer and introduction of measurement equipment are explained. This chapter also discusses with the process of preparation of sample and experimental method.

### 3.1 Magnetizer Circuit

In general, a simple magnetizer consists of a magnetic fixture and dc supply that supply the current for magnetic circuit. This work uses a bridge controlled rectifier to convert the ac voltage into dc voltage (called converter) as a dc supply. As mentioned earlier in **Chapter 2**, the phase controlled rectifier requires a control unit to control the timing of the firing angle, and turn on SCRs at the right time. The simple SCR-type magnetizer circuit diagram is shown in **Figure 3.1**. This work is a complementary of SCR-type, using SCR bridge to conduct the steady state current. The invented magnetizer is different from other research (in capacitor-type magnetizer) because the invented magnetizer, uses a steady state current to magnetize magnetic materials and has an additional inversion mode, which can reduce magnetizing current in a short time.



**Figure 3.1** The circuit diagram of a simple SCR-type magnetizer [9].

#### 3.1.1 Control Unit

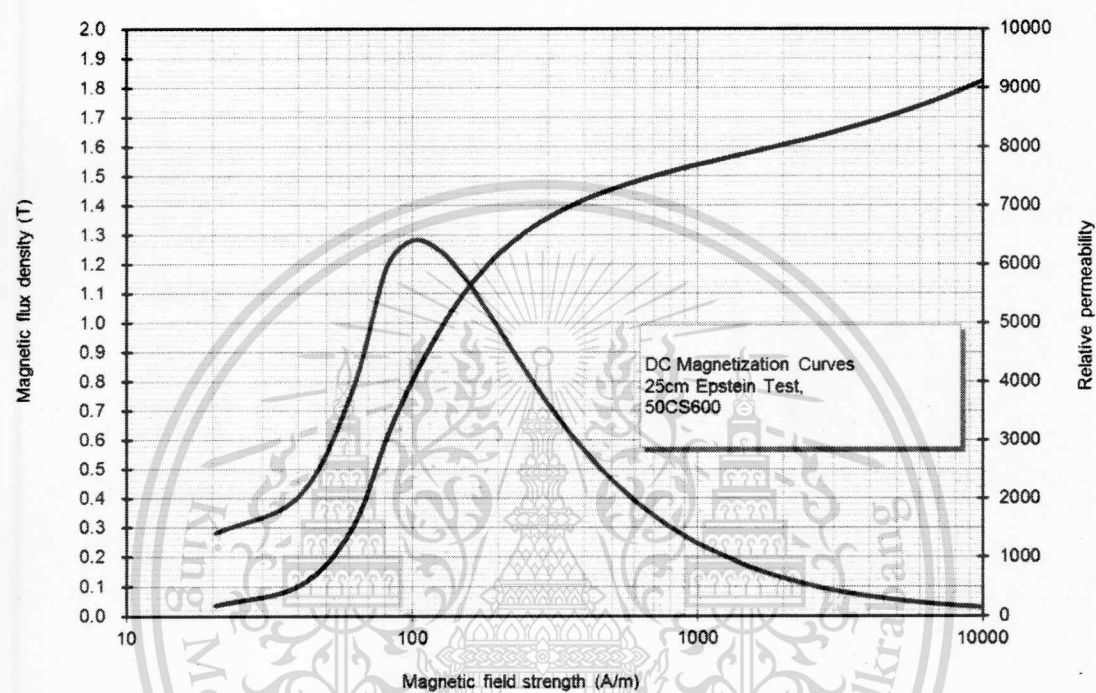
A microcontroller can be used as a control unit to read an input from a keypad, to display menu functions to LCD, to calculate concern parameters, to count the timer, and turn on SCRs (in bridge controlled rectifier). In the design, the magnetizer is aimed to have various outputs, so the

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variable can vary based on the input from keypad. Moreover, the output of this magnetizer is limited by a program input in order to prevent the over current, which can damage the wire wound according to Joule’s first law (the temperature of a conducting body may change when it carries a current). The programming of the microcontroller unit (MCU) is explained in **Section 3.2**, which is the process of designing, writing, testing and debugging of the program.



**Figure 3.2** Magnetization curve of the silicon steel 50CS600.

For the design of the control unit, it must ensure that the input is a desired flux density and the output is the average voltage from phase controlled converter. First, the expected magnetic flux density is selected from the constructed magnetizer. A silicon steel series 50CS600 (dedicated by Bangkok Pacific Steel) was used as a core materials, and the magnetization curve is shown in **Figure 3.2**.

Based on the curve shown in **Figure 3.2**, it was found that the flux density for the magnetizer can be used up to 1.8 T. Then, we calculated the required current was calculated by using **Equations 2.9, 2.20 and 2.21** in order to get the maximum flux density (value of 1.8 T)

$$I = \frac{\lambda}{L} \tag{3.1}$$

$$= \frac{N\Phi}{L} \tag{3.2}$$

$$= \frac{NBA}{L} \tag{3.3}$$

Where  $I$  is the required current from the desired flux density (A),  $L$  is the inductance of the magnetic fixture (H),  $N$  is the number of turns of the wound wire,  $B$  is the average flux density in the core (T) and  $A$  is the area of cross section of the core (m<sup>2</sup>).

In a magnetizer circuit diagram (**Figure 3.1**), the resistance is used to determine the output voltage of the converter. Then the average output from the phase controlled converter is calculated from using the *Ohm's law* which can be written as follows:

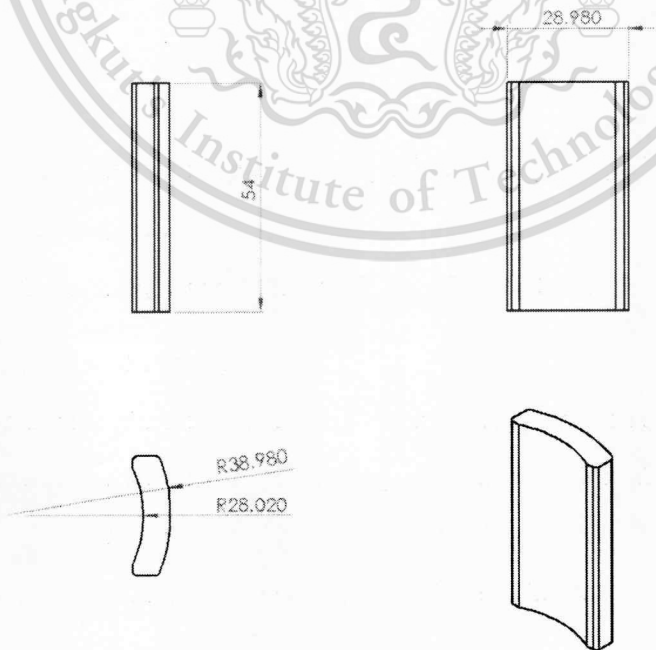
$$v_d = IR \tag{3.4}$$

Where  $R$  is the resistance of the magnetic fixture (Ohm),  $I$  is the required current from the desired flux density (A).

The value of  $L$ ,  $R$ ,  $N$  and  $A$  are explained in **Section 3.1.2**.

**3.1.2 Magnetic Fixture**

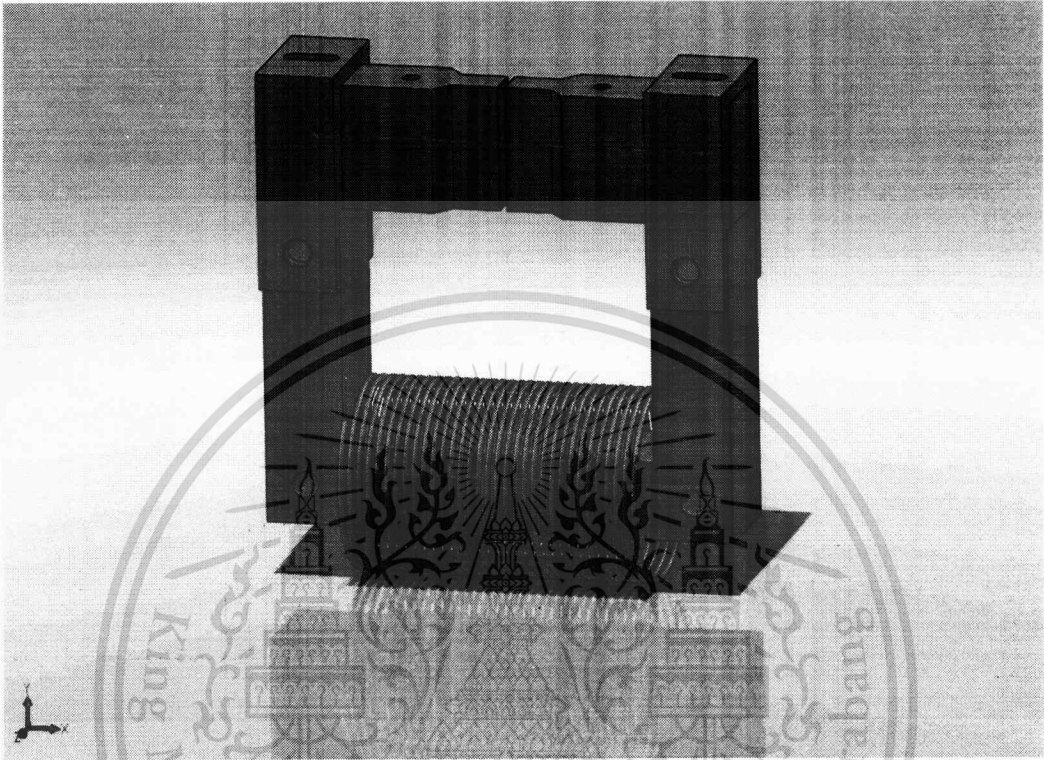
The magnetic fixture was designed to magnetize an arc-segment specimen, given in **Figure 3.3**. The silicon sheets used in this magnetic fixture were stacked, shaped into the desired shape, and assembled as the magnetic fixture shown in **Figure 3.4**. This preparation process used the wire-cut machine to cut the stacked sheets into three main parts.



**Figure 3.3** Dimension of the arc-segment specimen.

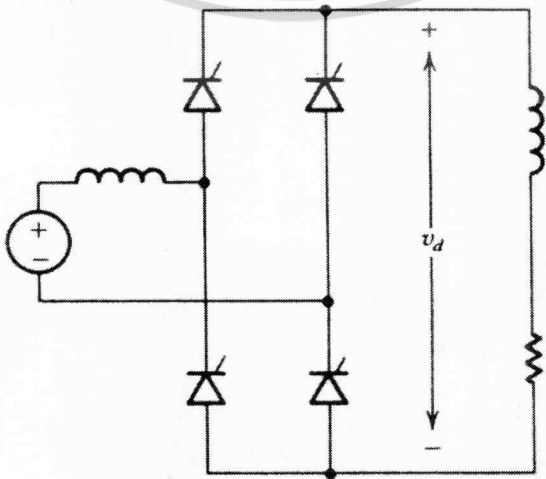


Next, the copper wire was wound around the fixture as shown in **Figure 3.4**. In this step, we determined the electrical properties of the fixture. The design of wound wire and its properties are explained in **Section 3.1.2.2**.



**Figure 3.4** Assemble magnetic fixture.

Since a typical magnetizing fixture is a type of fixed wire loops, its inductance can be modeled as a series R-L circuit, shown in **Figure 3.5**. The ac side reactance issue was considered as an issue of the commutating failure.



**Figure 3.5** The phase controlled magnetizer model [9].



The value of inductance, measured from RLC meter, is 0.521 H in series with the resistance of 8.375  $\Omega$ .

### 3.1.2.1 Core Material

Core material was selected from the relative permeability (**Table 2.1**). The higher relative permeability provides the higher flux density in the core (at the same current conducting through a coil). However, as there is a limitation of the resource supplier, so we selected a transformer core material to be our core magnetic fixture. The transformer core material has a relative permeability of 3500 and its magnetization curve behavior is shown in **Figure 3.2**.

### 3.1.2.2 Wire Gauge

An important factor for determining the wire gauge is its current-carrying capacity. The American Wire Gauge (AWG) is a standardized wire gauge system used since 1857. From the result of **Equation 3.1**, the required current for the desired flux density is 3 A. Then, we selected the wire gauge number of 19 AWG (#19, No. 19 AWG), which has a current capacity of 10 A.

The turns of wire were designed from the desired inductance and resistance of the magnetic fixture. At first, we measured the inductance from a 37-turn wound wire on the selected core. And the result was a 0.309 mH. Then, we applied this result with the designed turns (1500 turns) to get the new inductance as shown below.

$$\frac{0.309 \times 10^{-3} \text{ 37turns}}{37 \text{ 37turns}^2} = \frac{L_{\text{new}}}{\text{turns}_{\text{new}}^2} \quad (3.5)$$

$$L_{\text{new}} = 2.257 \times 10^{-7} \times 1500^2 \quad (3.6)$$

$$= 0.507 \text{ H} \quad (3.7)$$

And its resistance was determined by the wire length (No.19 AWG has resistance of 363.9  $\mu\Omega/\text{cm}$ ) as follows:

$$R_{\text{new}} = l_{1\text{turn}} \times \text{turns} \times R_{\text{wire}} \quad (3.8)$$

$$= 15.114 \times 1500 \times 363.9 \times 10^{-6} \quad (3.9)$$

$$= 8.25 \Omega \quad (3.10)$$

Where  $L_{\text{new}}$  is the inductance of designed turns (of magnetic fixture),  $R_{\text{new}}$  is the resistance of designed turns (of magnetic fixture),  $l_{1\text{turn}}$  is length of wire in one turn wound over the core (cm), and  $R_{\text{wire}}$  is resistance of a wire ( $\mu\Omega/\text{cm}$ ).

Then the 1500 turns of No. 19 AWG wire, wound in the magnetic fixture, had an inductance of 0.507 H and resistance of 8.25  $\Omega$  (numerical analysis). These results showed a good agreement with the value measured by the RLC meter.

**Table 3.1** summarizes the limitation of the phase-controlled magnetizer. The inductance, resistance, average output load voltage and average output load current values are from measurement (actual values). The maximum magnetizing field was limited by the saturation value of silicon steel core. The metal coil-core structure has an advantage of low power supply can provides high magnetic flux density. Nonetheless, the magnetic flux density of the coil-core was limited by its own properties.

**Table 3.1** Limitation of the invented magnetizer

| Parameters                | Limited Value |
|---------------------------|---------------|
| Inductance (Henry)        | 0.521         |
| Resistance (Ohm)          | 8.375         |
| Magnetizing Field (Tesla) | 1.60          |
| Peak Input AC Voltage (V) | 311.12        |
| Average Load Voltage      | 172.10        |
| Average Load Current      | 28.92         |

3.2 Microcontroller

Recent microcontrollers use the flash-based program memory that is electrically erasable. This means that the device can be reprogrammed in the circuit.

Required equipments are as follows:

- Programmer/debugger and software for PC
- Software assembler
- Target board and adaptor

This project, used ET-PGMPIC USB V2.0 as a programmer/debugger, CCS free student version as a software assembler, and ET-PGM PIC TEXTTOOLS as a target board adaptor. Also, we used a PIC16F887 microcontroller, which has a flash program memory 8021 words, EEPROM data memory 256 bytes, 2 timers 8-bit and 1 timer 16-bit, and 35 I/O.

Microcontroller received an input of the desired magnetic flux density (to magnetize specimen in magnetic fixture) from a keypad 4x4 (4 rows with 4 columns), and from transformer 24 V (to INT; interrupt pin input). The outputs of the microcontroller were a control signal to switch on SCRs driver and a 16x2 characters (16-bit 2 rows) LCD display. The input and output from microcontroller unit are shown in **Figure 3.6**.



**Figure 3.6** Input and output of the microcontroller unit.

Microcontrollers are traditionally programmed in assembly language. Each type having its own syntax, which translates directly into machine code. Programming PIC microcontroller in C language can save the development time. The C language eliminates the need to learn the assembly language. Still, it is necessary to understand the architecture. Clocking options, peripherals sets, and pin multiplexing issues still need to be solved. After having completed the programming, the program can be tested in Proteus. The use of Proteus simulator will allow us to complete the designed system while help saving time and on prototype PCB.

### 3.2.1 C Program Basics

The purposes of an embedded program are to read in data or control inputs, process them, and operate the outputs as required. The input from parallel, serial, and analog ports are held in the file registers for temporary storage and processing. And the results e.g. data or a signal are output later on. The program for processing the data usually contains repetitive loops and conditional branching, which depends on an input or calculated value.

#### 3.2.1.1 Variables

Most programs need to name the variables to hold their values. A variable name is a label attached to the memory location where the variable value is stored. When working in assembly, a



register label acts as the variable name and has to be assigned explicitly. In C, the variable label is automatically assigned to the next available location or locations. The variable name and type must be declared at the start of the program block, so that the compiler can allocate a corresponding set of locations. Variable values are assumed to be in decimal by default.

### **3.2.1.2 Looping**

Most real-time applications need to be executed continuously until the processor turns off or resets. Therefore, the program generally jumps back at the end to repeat the main control loop. In C, this can be implemented as a “while” loop.

### **3.2.1.3 Decisions**

The simplest way to illustrate basic decision making is to change an output depending on the state of an input.

## **3.2.2 Program Operation**

As in an introduction section, the objective is to study effects of magnetization in permanent magnet properties. The magnetization process can be differently made in two modes; (1) rectification mode following with an inversion mode and (2) rectification mode without an inversion mode.

### **3.2.2.1 Rectification Mode following with an Inversion Mode**

The microcontroller was designed to operate in rectification mode for a steady state magnetizing current. Then following with an inversion mode, which will decay the current to zero in a short time. As explained earlier, the inversion mode is operated in an inversion region which has the firing angle close to  $180^\circ$ . At a certain firing angle, it produces the maximum negative voltage which consequently decay the current in a short time.

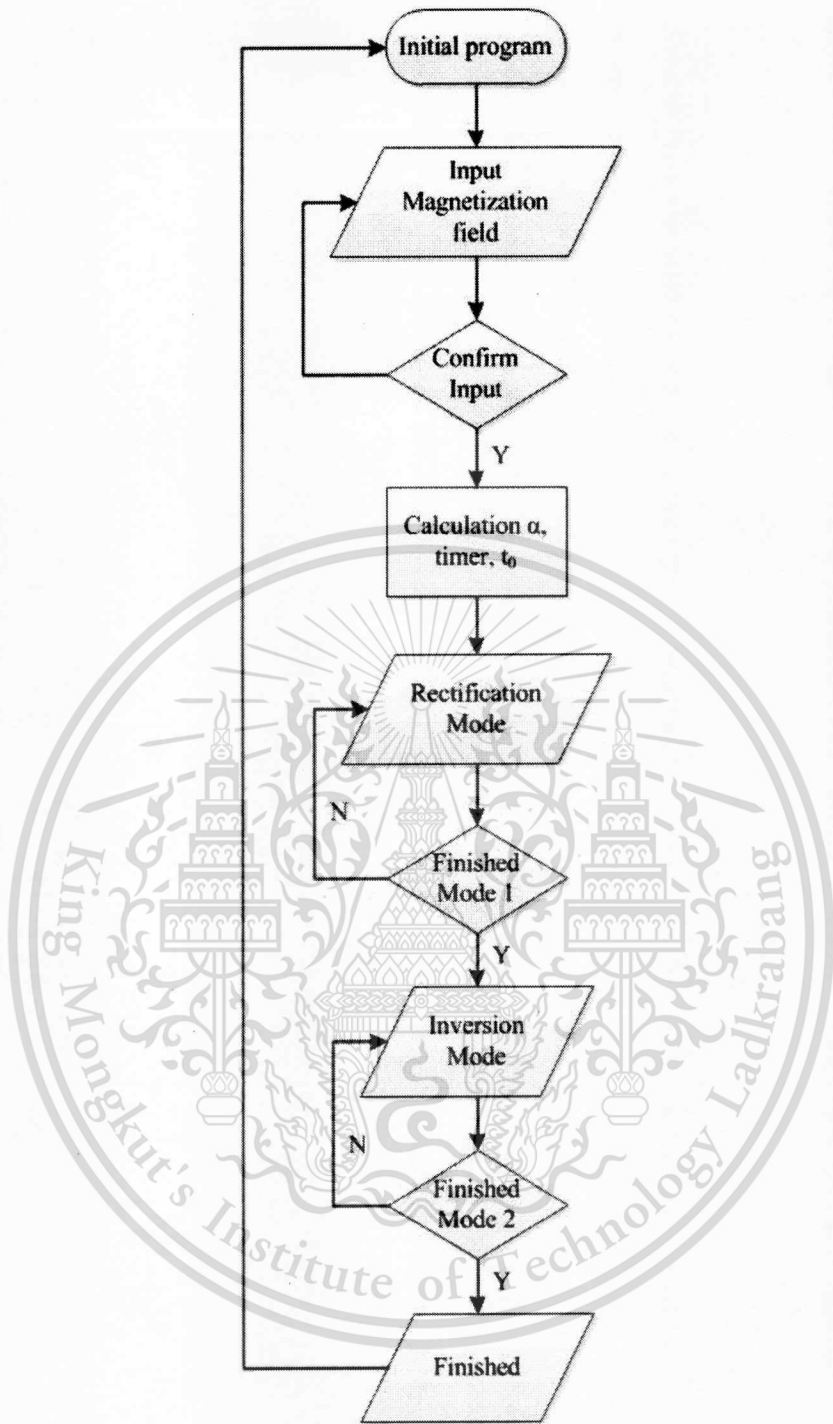
### **3.2.2.2 Rectification Mode without an Inversion Mode**

In this mode, the microcontroller will operate in rectification mode only (without an inversion mode), then it will finish the program. This mode was designed to compare between the results from magnetizing in the rectification mode with an inversion mode, and those from magnetizing in the rectification mode without an inversion mode. The expected results were guessed that magnetizing with an additional inversion mode would give an advantage to magnetic properties.

### 3.2.3 Programming

We already know that the inputs to microcontroller for this work are an input from a keypad and from transformer. In preceding section, the variable must be declared at the start of the program. Once entering into the main program (read an input from keypad to set the value of the desired magnetize magnetic flux density), then calculate the concern parameters, which consist of output voltage, current, firing angle and timers. After that, the microcontroller will automatically operate the program operation. When processes are finished, the program will go back to the start and wait for a new input value of magnetizing field. Flowchart of the program is shown in **Figure 3.7**.





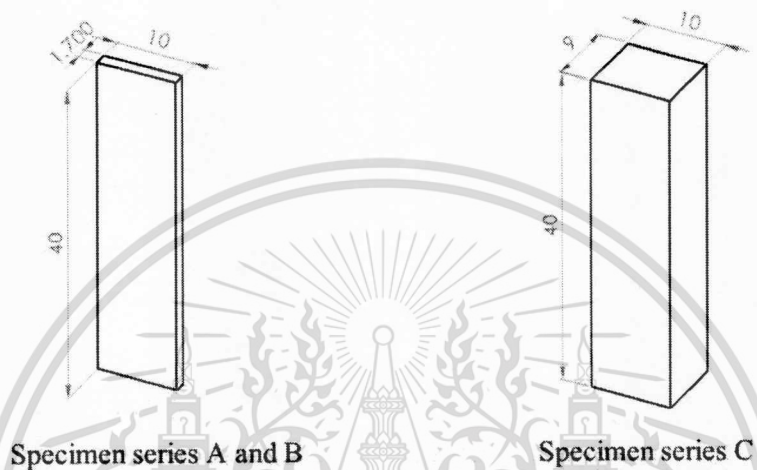
**Figure 3.7** Flowchart of the program in microcontroller.

If the compiler complies the program without an errors, then the simulation of the program will make in Proteus. This is the process of testing and debugging. The firing angle and output signal were checked and calibrated to improve the magnetizer performance.



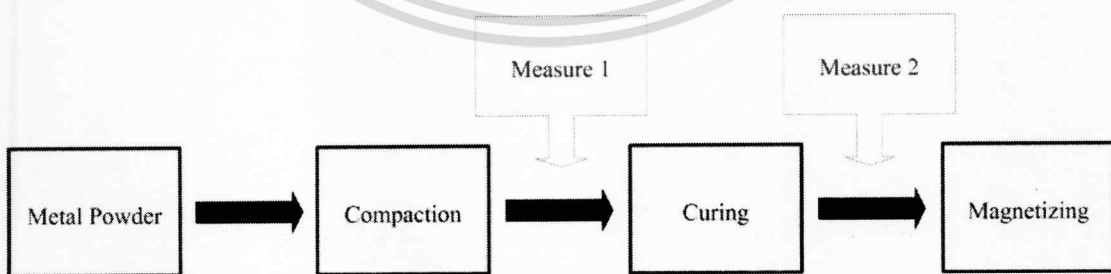
### 3.3 Preparation of Sample

As shown in the **Figure 3.3**, the actual model of specimen is an arc-segment. Due to the limitation of equipment, a specimen dimension in this experiment was designed in a rectangular shape as shown in **Figure 3.8** in order to fit with the gap of magnetizer (see **Figure 3.4**).



**Figure 3.8** Dimension of the rectangular shape specimen.

The preparation process for metal powder, was conducted by IMT manufacturing is the rapid quenching, which yields an isotropic material. Then this material was formed into a specimen by the compaction moulding. Next, in the curing process, a green specimen was put in a furnace of 170°C (degree of Celsius) for 20 minutes. Finally, the specimen was magnetized and said that it is a permanent magnet. The diagram of preparation process is shown in **Figure 3.9**.



**Figure 3.9** P/M process for bonded neodymium magnet application.

### 3.4 Experimental Method

The experiments for this work were designed based on the following hypothesis:

- The phase-controlled magnetizer
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- P/M process
- Permanent magnets application

Before starting the experiment, we had to invent the magnetizer first, then we measured and improved its performance. Finally, we studied the effects of magnetizing field on the properties of permanent magnets.

### 3.4.1 Magnetizer Performance

The outputs of microcontroller unit are signals that control the SCRs to turn on at the right time in the cycle (firing angle) and this results in the power conversion from ac to dc side. So, the outputs of this magnetizer are a voltage and current that were drive into the magnetic fixture.

#### 3.4.1.1 Firing Angle

The firing angle was measured by oscilloscope (2 channels), which shows an output signal from microcontroller, compared to an input from transformer. This firing angle value was computed from **Equation 2.1** by input of the desired flux density.

#### 3.4.1.2 Voltage and Current

The firing angle controls the output voltage of the invented magnetizer. The output voltage was computed from **Equation 2.1** and measured by digital multimeter. The multimeter measured dc voltage across the load terminal that is the average voltage. The current was also measured by digital multimeter that was connected in series to the magnetic fixture terminal and compared to the ohm's law.

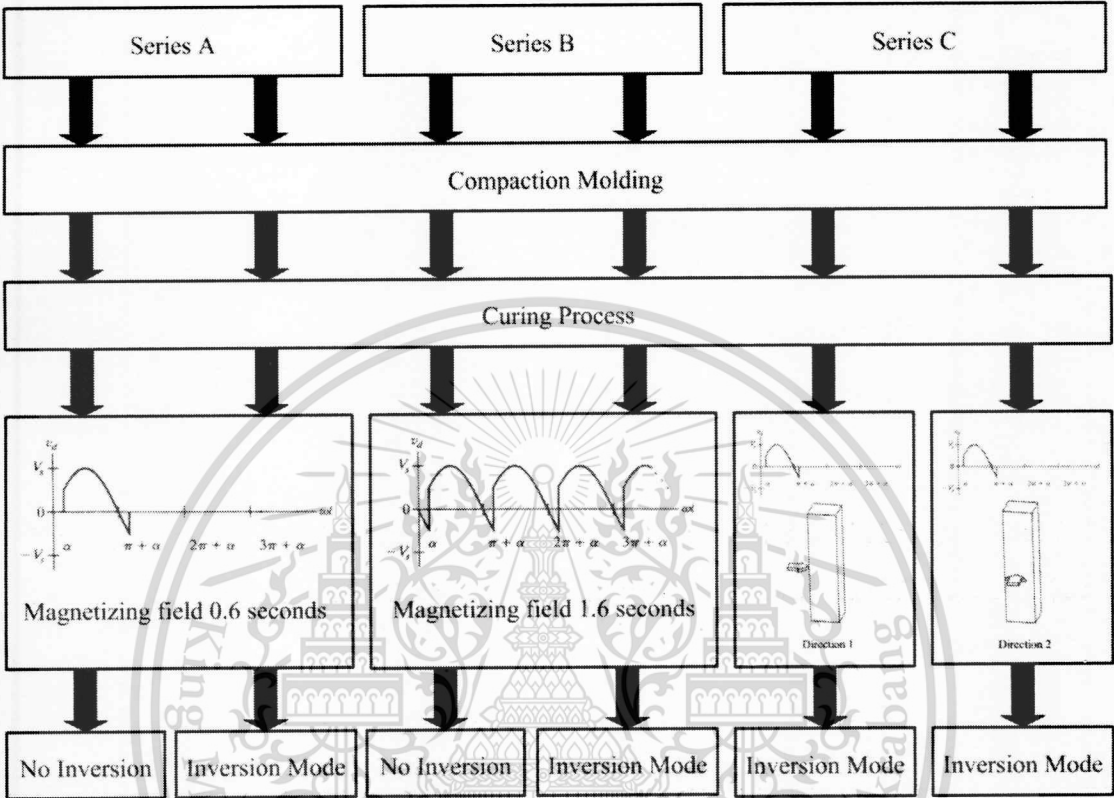
#### 3.4.1.3 Magnetic Flux Density

Tesla meter was used to measure the magnetic flux density (magnetic intensity), produced by this magnetizer and can be measured at the air gap.

### 3.4.2 Effect of Magnetization in Permanent Magnet Properties

As mentioned in **Chapter 2**, there is an additional state called inversion mode. This experiment had conducted three series of specimen to compare their properties. After the powder was compacted and passed through the curing process, specimens will be magnetized by the invented magnetizer. Schematic for study effects of magnetization is shown in **Figure 3.10**. The first series, named A, will be magnetized for 0.6 seconds, which is referral a standard duration, of magnetizing field with/without inversion mode. Specimen series B will be magnetized for longer

duration (1.6 seconds) with/without inversion mode. Specimen series C will be magnetized (with inversion mode) in different directions. Note that each condition was conducted three times (three specimens).



**Figure 3.10** Schematic for study effect of magnetization.



## CHAPTER 4

### RESULTS AND DISCUSSIONS

In this chapter, the magnetizer performances: firing angle, voltage, current, and magnetic flux density, are reported. After constructing and improving a phase-controlled magnetizer, the experiment was conducted to study the effects of magnetization on the permanent magnet properties. Results and discussions were also given in this chapter.

#### 4.1 Magnetizer Performance

As prescribed in **Section 3.1.2**, one of the outputs of the invented magnetizer is a signal control, which can be measured in the terms of voltage and current. But the first inspection is to investigate the firing angle and calibrate the control system before testing.

##### 4.1.1 Firing Angle

The firing angle was calculated in the program, using the following equation derived from **Equation 2.1**, **Equation 3.3** and **Equation 3.4**;

$$v_d = \frac{2V_s}{\pi} \cos \alpha \quad (2.1)$$

$$I = \frac{NBA}{L} \quad (3.3)$$

$$v_d = IR \quad (3.4)$$

A relationship between the firing angle and the average value output of phase controlled converter can be explained by **Equation 2.1**. The average output current from this magnetizer was controlled by magnetic fixture resistance as in **Equation 3.4**. And a relationship between the linkage flux and the inductance is illustrated in **Equation 3.3**. These equations can be summarized into the following equation:

$$\alpha = \cos^{-1} \left( \frac{NBA \times R \times \pi}{L \times 2V_s} \right) \quad (4.1)$$

Where  $N$  is 1500 turns,  $B$  is input flux density T,  $A$  is  $0.0005276 \text{ m}^2$ ,  $L$  is 0.507 H,  $R$  is  $8.25 \Omega$  and  $V_s$  is 67.88 V. The calculated values from program calculation were summarized in **Table 4.1**. For example, suppose that we input the desired magnetic flux density of 0.5 T (in row no.9), then we would get the firing angle of  $81.5^\circ$ , synchronizing with the ac line.

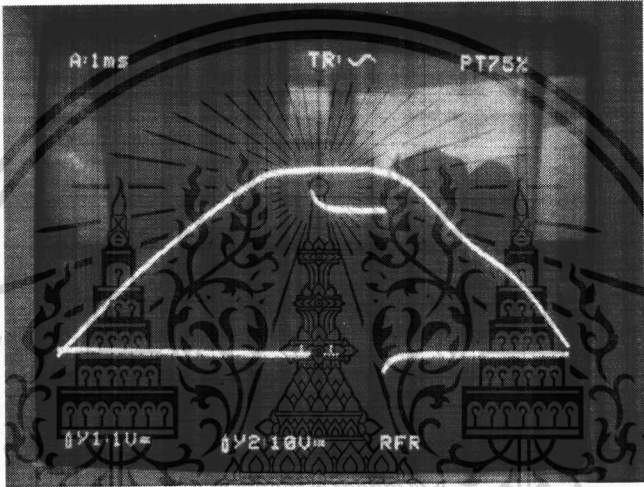
**Table 4.1** Calculated values from program calculation.

| <b>B (T)</b> | <b><math>\lambda</math>(Wb)</b> | <b>Current (A)</b> | <b>Voltage (V)</b> | <b>Firing Angle (°)</b> |
|--------------|---------------------------------|--------------------|--------------------|-------------------------|
| 0.10         | 0.07                            | 0.15               | 1.27               | 88.3                    |
| 0.15         | 0.11                            | 0.22               | 1.90               | 87.4                    |
| 0.20         | 0.15                            | 0.30               | 2.54               | 86.6                    |
| 0.25         | 0.19                            | 0.37               | 3.18               | 85.7                    |
| 0.30         | 0.23                            | 0.45               | 3.81               | 84.9                    |
| 0.35         | 0.27                            | 0.53               | 4.45               | 84                      |
| 0.40         | 0.31                            | 0.60               | 5.08               | 83.2                    |
| 0.45         | 0.35                            | 0.68               | 5.72               | 82.3                    |
| 0.50         | 0.39                            | 0.75               | 6.36               | 81.5                    |
| 0.55         | 0.43                            | 0.83               | 6.99               | 80.6                    |
| 0.60         | 0.47                            | 0.91               | 7.63               | 79.8                    |
| 0.65         | 0.51                            | 0.98               | 8.26               | 78.9                    |
| 0.70         | 0.55                            | 1.06               | 8.90               | 78.1                    |
| 0.75         | 0.59                            | 1.23               | 9.54               | 77.2                    |
| 0.80         | 0.63                            | 1.21               | 10.17              | 76.3                    |
| 0.85         | 0.67                            | 1.29               | 10.81              | 75.5                    |
| 0.90         | 0.71                            | 1.36               | 11.44              | 74.6                    |
| 0.95         | 0.75                            | 1.44               | 12.08              | 73.7                    |
| 1.00         | 0.79                            | 1.51               | 12.72              | 72.8                    |
| 1.05         | 0.83                            | 1.59               | 13.35              | 71.9                    |
| 1.10         | 0.87                            | 1.67               | 13.99              | 71.1                    |
| 1.15         | 0.91                            | 1.74               | 14.62              | 70.2                    |
| 1.20         | 0.94                            | 1.82               | 15.26              | 69.3                    |
| 1.25         | 0.98                            | 1.89               | 15.90              | 68.4                    |
| 1.30         | 1.02                            | 1.97               | 16.53              | 67.4                    |
| 1.35         | 1.06                            | 2.05               | 17.17              | 66.5                    |
| 1.40         | 1.10                            | 2.12               | 17.81              | 65.6                    |
| 1.45         | 1.14                            | 2.20               | 18.44              | 64.7                    |
| 1.50         | 1.18                            | 2.27               | 19.08              | 63.7                    |
| 1.55         | 1.22                            | 2.35               | 19.71              | 62.8                    |

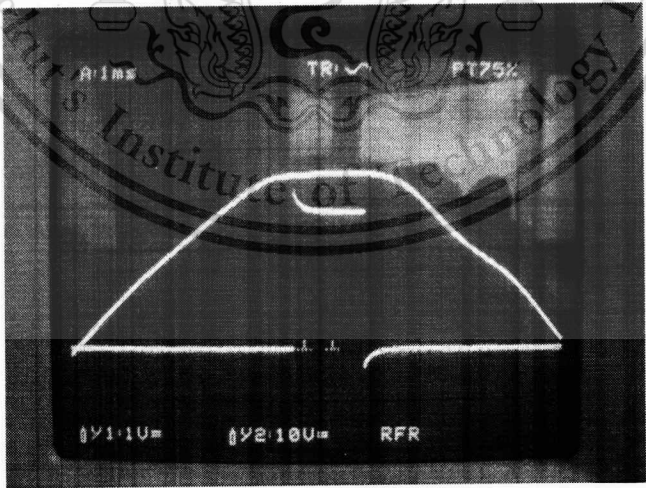
**Table 4.1** Calculated values from program calculation (cont.).

| B (T) | $\lambda$ (Wb) | Current (A) | Voltage (V) | Firing Angle (°) |
|-------|----------------|-------------|-------------|------------------|
| 1.60  | 1.26           | 2.43        | 20.35       | 61.9             |
| 1.65  | 1.30           | 2.50        | 20.99       | 60.9             |

The firing angle, investigated by oscilloscope 2-ch, can determine the phase shift (of a various input) of a control signal, synchronizing with the ac load line as shown in **Figure 4.1** to **Figure 4.4**.

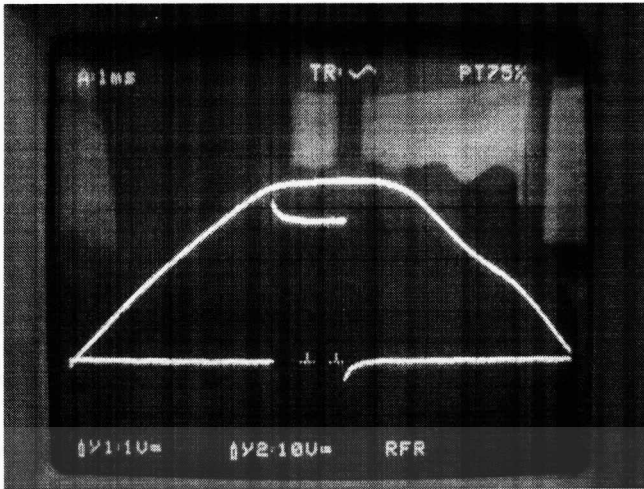


**Figure 4.1** Control signal when input 0.10 T (firing angle,  $\alpha = 88.3^\circ$ ).

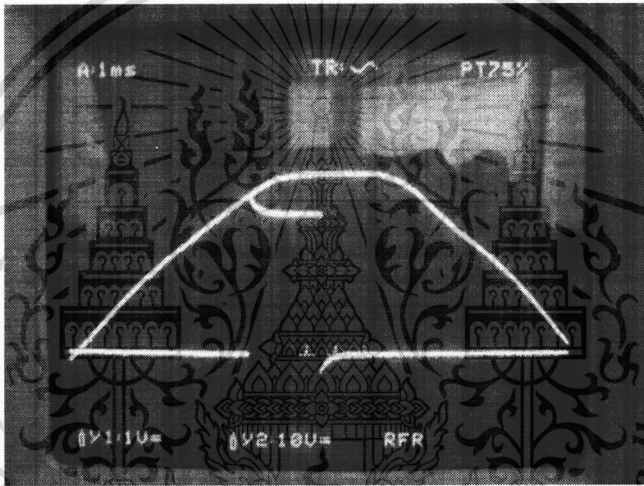


**Figure 4.2** Control signal when input 0.50 T (firing angle,  $\alpha = 81.5^\circ$ ).





**Figure 4.3** Control signal when input 1.00 T (firing angle,  $\alpha = 72.8^\circ$ ).



**Figure 4.4** Control signal when input 1.50 T (firing angle,  $\alpha = 63.7^\circ$ ).

At first, the 48 V of ac line was used as an input to the interrupt pin. It showed an error control from a noise of switching. This problem was eliminated by the use of isolated transformer as an input to the interrupt pin. Another transformer (12V) was used and showed a delay of 17 degrees, synchronizing with the ac line. This delay can be explained by the comparator component in the microcontroller interrupt pin input. If the rate of increasing voltage is low, it will result in a delay in a zero crossing detection. But if the 12V is replaced with 24V, the difference was reduced to 8 degrees. This experiment showed that the higher voltage input to the interrupt pin provided a higher precision of the firing angle.

The diagram for interrupt pin is shown in **Figure 4.5**. From I/O pin to the RB0/INT, the signal passed through the comparator. The 24 V transformer had an increasing rate of 4.8 V/ms which was 2 times higher than the increasing rate of 12 V transformer (2.4 V/ms). According to the results, we suggest that the higher voltage input to the interrupt pin, the better.





were compared to the calculated values that were calculated in the program. The actual voltage and current showed a good agreement with values from the program calculation.

**Table 4.2** Comparison of calculation and measured values of output voltage and current.

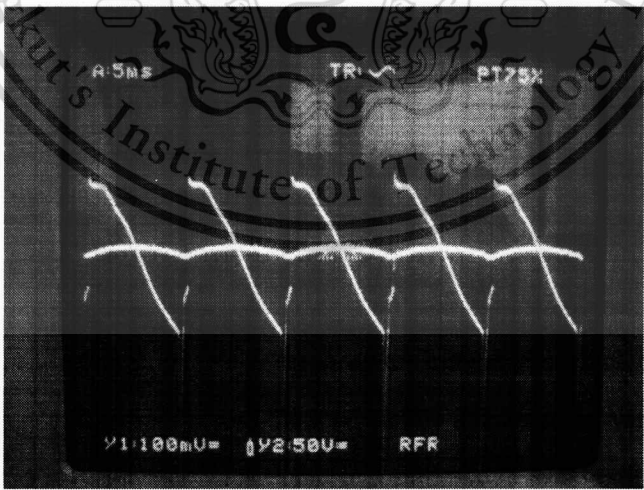
| <b>Flux Density<br/>(T)</b> | <b>Calculation<br/>Current (A)</b> | <b>Measured<br/>Current (A)</b> | <b>Calculation<br/>Voltage (V)</b> | <b>Measured<br/>Voltage (V)</b> |
|-----------------------------|------------------------------------|---------------------------------|------------------------------------|---------------------------------|
| 0.10                        | 0.151                              | 0.117                           | 1.272                              | 3.84                            |
| 0.15                        | 0.227                              | 0.124                           | 1.908                              | 4.12                            |
| 0.20                        | 0.303                              | 0.127                           | 2.544                              | 4.12                            |
| 0.25                        | 0.379                              | 0.130                           | 3.180                              | 4.12                            |
| 0.30                        | 0.455                              | 0.711                           | 3.816                              | 5.13                            |
| 0.35                        | 0.531                              | 0.832                           | 4.452                              | 5.48                            |
| 0.40                        | 0.607                              | 0.887                           | 5.088                              | 6.20                            |
| 0.45                        | 0.683                              | 1.026                           | 5.724                              | 6.46                            |
| 0.50                        | 0.759                              | 1.153                           | 6.360                              | 7.09                            |
| 0.55                        | 0.835                              | 1.246                           | 6.996                              | 7.82                            |
| 0.60                        | 0.911                              | 1.348                           | 7.632                              | 8.23                            |
| 0.65                        | 0.987                              | 1.447                           | 8.269                              | 9.08                            |
| 0.70                        | 1.063                              | 1.564                           | 8.905                              | 9.50                            |
| 0.75                        | 1.139                              | 1.669                           | 9.541                              | 10.31                           |
| 0.80                        | 1.215                              | 1.765                           | 10.177                             | 10.94                           |
| 0.85                        | 1.291                              | 1.861                           | 10.813                             | 11.64                           |
| 0.90                        | 1.367                              | 1.910                           | 11.449                             | 11.88                           |
| 0.95                        | 1.443                              | 1.991                           | 12.085                             | 12.22                           |
| 1.00                        | 1.519                              | 2.096                           | 12.721                             | 12.91                           |
| 1.05                        | 1.594                              | 2.148                           | 13.357                             | 13.42                           |
| 1.10                        | 1.670                              | 2.272                           | 13.993                             | 14.31                           |
| 1.15                        | 1.746                              | 2.368                           | 14.629                             | 15.01                           |
| 1.20                        | 1.822                              | 2.458                           | 15.265                             | 15.46                           |
| 1.25                        | 1.898                              | 2.569                           | 15.902                             | 16.19                           |
| 1.30                        | 1.974                              | 2.665                           | 16.538                             | 16.83                           |



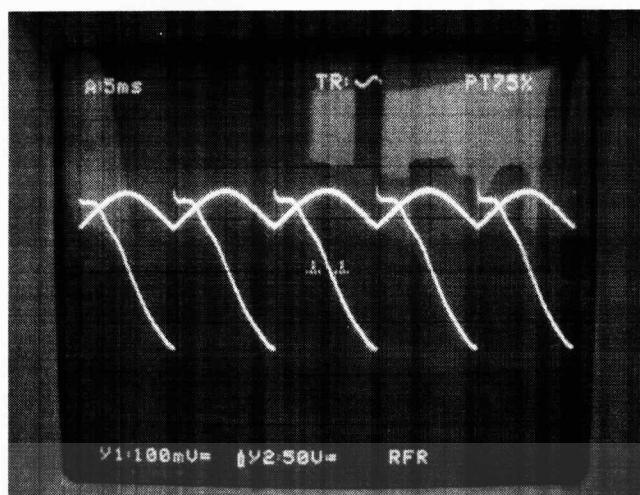
**Table 4.2** Comparison of calculation and measured values of output voltage and Current (cont.).

| Flux Density<br>(T) | Calculation<br>Current (A) | Measured<br>Current (A) | Calculation<br>Voltage (V) | Measured<br>Voltage (V) |
|---------------------|----------------------------|-------------------------|----------------------------|-------------------------|
| 1.35                | 2.050                      | 2.754                   | 17.174                     | 17.38                   |
| 1.40                | 2.126                      | 2.850                   | 17.810                     | 17.71                   |
| 1.45                | 2.202                      | 2.965                   | 18.446                     | 18.52                   |
| 1.50                | 2.278                      | 3.054                   | 19.082                     | 19.06                   |
| 1.55                | 2.354                      | 3.135                   | 19.718                     | 19.56                   |
| 1.60                | 2.430                      | 3.221                   | 20.354                     | 20.14                   |
| 1.65                | 2.506                      | 3.302                   | 20.990                     | 20.54                   |

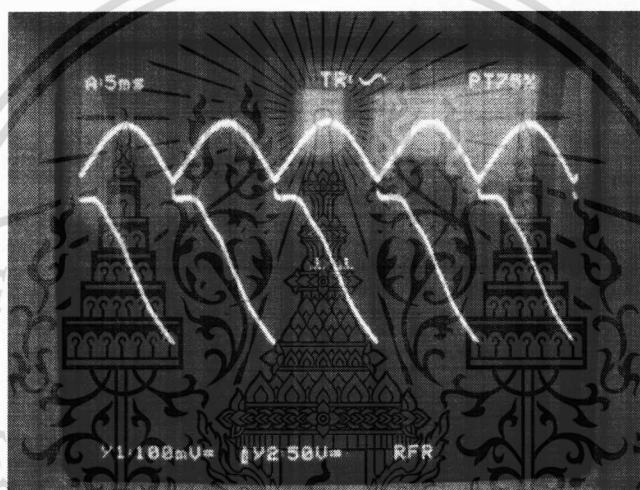
The current and voltage, generally response to firing angle, which can be explained by **Equation 4.1**. Voltage and current across the load can be alternated by varying a firing angle. The signals across the load were also measured by oscilloscope to investigate the behavior of the coil. The signal shape of voltage and current, operating in rectification mode at a various input, are shown in **Figure 4.6** to **Figure 4.9**. The current was measured by the current probe which operated at 100 mV/A.



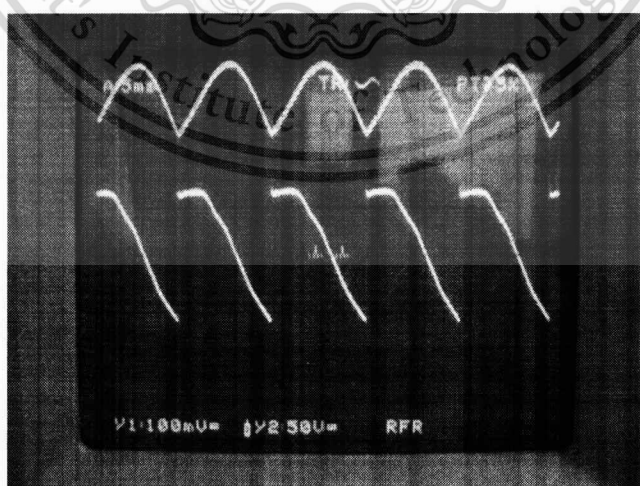
**Figure 4.6** Voltage and current across the load when input 0.10 T (firing angle,  $\alpha = 88.3^\circ$ ).



**Figure 4.7** Voltage and current across the load when input 0.50 T (firing angle,  $\alpha = 81.5^\circ$ ).



**Figure 4.8** Voltage and current across the load when input 1.00 T (firing angle,  $\alpha = 72.8^\circ$ ).



**Figure 4.9** Voltage and current across the load when input 1.50 T (firing angle,  $\alpha = 63.7^\circ$ ).

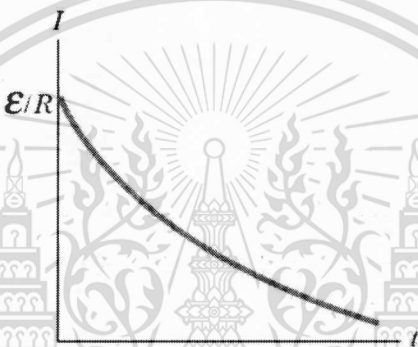
These results can be explained by considering the average voltage on phase controlled converter in the rectification region. It appeared that current of firing angle between  $80^\circ$  and  $90^\circ$



were not constant seeing that the current level had reached zero (see **Figure 4.6**). This may be explained by the time constant of the R-L circuit as in **Equation 2.78**;

$$I = \frac{\varepsilon}{R} e^{-tR/L}$$

The energy, stored in an inductance, is not enough to oppose the change of current until the next cycle is reach. So the current level dropped and can be said that it did not continue at the certain firing angle. If the initial current of natural response is low, the current level will drop to zero in a short time, as illustrated in **Figure 4.10**.



**Figure 4.10** R-L circuit natural response [30].

**4.1.3 Magnetic Flux Density**

Tesla meter was applied at the air gap. The air gap, in this experiment had 4 mm width, which resulted in a magnetic induction shown in **Table 4.3**.

**Table 4.3** Magnetic Induction of the Phase-controlled Magnetizer.

| Input Flux Density<br>(T) | Magnetic Induction<br>(mT) | Measured Current<br>(A) | Measured Voltage<br>(V) |
|---------------------------|----------------------------|-------------------------|-------------------------|
| 0.10                      | 31                         | 0.117                   | 3.84                    |
| 0.15                      | 32                         | 0.124                   | 4.12                    |
| 0.20                      | 32                         | 0.127                   | 4.12                    |
| 0.25                      | 33                         | 0.130                   | 4.12                    |
| 0.30                      | 186                        | 0.711                   | 5.13                    |
| 0.35                      | 205                        | 0.832                   | 5.48                    |
| 0.40                      | 219                        | 0.887                   | 6.20                    |
| 0.45                      | 231                        | 1.026                   | 6.46                    |



**Table 4.3** Magnetic Induction of the Phase-controlled Magnetizer (cont.).

| Input Flux Density<br>(T) | Magnetic Induction<br>(mT) | Measured Current<br>(A) | Measured Voltage<br>(V) |
|---------------------------|----------------------------|-------------------------|-------------------------|
| 0.50                      | 242                        | 1.153                   | 7.09                    |
| 0.55                      | 249                        | 1.246                   | 7.82                    |
| 0.60                      | 256                        | 1.348                   | 8.23                    |
| 0.65                      | 264                        | 1.447                   | 9.08                    |
| 0.70                      | 270                        | 1.564                   | 9.50                    |
| 0.75                      | 276                        | 1.669                   | 10.31                   |
| 0.80                      | 282                        | 1.765                   | 10.94                   |
| 0.85                      | 286                        | 1.861                   | 11.64                   |
| 0.90                      | 290                        | 1.910                   | 11.88                   |
| 0.95                      | 292                        | 1.991                   | 12.22                   |
| 1.00                      | 297                        | 2.096                   | 12.91                   |
| 1.05                      | 302                        | 2.148                   | 13.42                   |
| 1.10                      | 308                        | 2.272                   | 14.31                   |
| 1.15                      | 312                        | 2.368                   | 15.01                   |
| 1.20                      | 317                        | 2.458                   | 15.46                   |
| 1.25                      | 321                        | 2.569                   | 16.19                   |
| 1.30                      | 325                        | 2.665                   | 16.83                   |
| 1.35                      | 328                        | 2.754                   | 17.38                   |
| 1.40                      | 332                        | 2.850                   | 17.71                   |
| 1.45                      | 335                        | 2.965                   | 18.52                   |
| 1.50                      | 338                        | 3.054                   | 19.06                   |
| 1.55                      | 340                        | 3.135                   | 19.56                   |
| 1.60                      | 343                        | 3.221                   | 20.14                   |
| 1.65                      | 349                        | 3.302                   | 20.54                   |

These results presented magnetic induction that would apply to the specimens. These values were relatively low, so the magnetizer was improved to reach the possible maximum value it could provide (close to core saturation at the gap). The 220V was re-applied to the ac load line. (this also needed to re-generated the program code). This helped increase the current

up to 20A. The magnetic induction, a new current and voltage were investigated, shown in **Table 4.4** (2 mm air gap). The results illustrated an improvement of magnetic induction, compared to previously results.

As the certain problem of discontinued current, the improved magnetizer has been investigated and found that in the range of 0-6 T of input flux density (firing angle of 60-90 degree) also showed the same problem. The inspection of magnetic flux density was reconsidered to operate at 7-15 T.

**Table 4.4** Magnetic Induction of the improved Phase-controlled Magnetizer.

| Input Flux Density<br>(T) | Magnetic Induction<br>(mT) | Measured Current<br>(A) | Measured Voltage<br>(V) |
|---------------------------|----------------------------|-------------------------|-------------------------|
| 7                         | 794                        | 15.52                   | 88.0                    |
| 8                         | 820                        | 17.16                   | 98.9                    |
| 9                         | 847                        | 18.55                   | 110.1                   |
| 10                        | 866                        | 20.26                   | 120.2                   |
| 11                        | 898                        | 22.56                   | 132.4                   |
| 12                        | 919                        | 24.33                   | 143.1                   |
| 13                        | 937                        | 25.87                   | 152.5                   |
| 14                        | 964                        | 27.37                   | 161.5                   |
| 15                        | 979                        | 28.92                   | 172.1                   |

This experiment revealed that the width of air gap was significantly related to the magnetic induction. Ferahani and Razi [4] had studied the effect of air gap on the magnetizer operation. By varying the air gap, the inductance and energy of coil have changed [4]. Therefore, this can be explained by following equation:

$$L = \frac{N^2}{l/\mu A} \tag{2.22}$$

Where  $L$  is the inductance of magnetic fixture,  $N$  is the number of turn,  $l$  is the length of core section response to  $A$ ,  $\mu$  is the permeability of core and  $A$  is the area of cross section of core.

The inductance is a function of length of core section, which responses to the area of cross section of core, is shown in **Equation 2.22**. The length of core section has a reverse

variation to its inductance. For the designed magnetic fixture (**Figure 3.4**), if the length of the air gap increases, the inductance will decrease its value. The desired inductance was expected to get the highest value which would give high time constant for the magnetic fixture.

It appeared that the inductance of coil had a direct relationship to the gap length. By decreasing the air gap, the inductance of coil will increase [4]. In addition, the result of Ferahani and Razi [4] illustrated that the magnetic flux density at the gap had been increasing slightly by decreasing air gap width. This can be explained by the following equation:

$$B_g = \left( \frac{Ni - \frac{B_c l_c}{\mu_c}}{l_g} \right) \mu_0 \quad (4.2)$$

**Equation 4.2** was derived from **Equation 2.6a**. The magnetomotive force is a function of the magnetic field multiply by length of magnetic path. From superposition principle states that the magnetomotive force due to many core permeability is the vector sum of the magnetomotive forces, produced by individual core permeability.

The magnetic flux density for this experiment that had the air gap length of 2 mm was measured. It appeared that the magnetic flux density had a fringing flux loss at this value of air gap length. This had resulted in the limitation of maximum value of magnetizing field that was applied to specimens.

$$H_c l_c + H_g l_g = \sum Ni \quad (4.3)$$

Another aspect of the invented magnetizer is a flux density of 1 T can be obtained with relatively low current of 28 A, compared to 1000 A [4] and 1600 A [5]. The result implied the advantage of this magnetizer. Thus, this advantage can be explained by the application of soft magnetic used as a core in electromagnet. Soft magnetic materials have high initial permeability at low coercivity. These properties may reach its saturation magnetization with a relatively low applied field [12].

## 4.2 Effect of Magnetization in Permanent Magnet Properties

This experiment had investigated on how the magnetic properties of specimens react to the magnetizing field by following the schematic as shown in **Figure 3.10**. Three set of specimens, named series A, B and C, were magnetized by various profiles of magnetizing field. Each set of specimens, were divided into three groups, and magnetized by magnetizing field of



8 T, 12 T and 15 T respectively. Each state was conducted three times. Specimens in series A were magnetized by continuous pulse of magnetizing field for 0.6 seconds with/without inversion mode (The magnetizing signals are shown in **Figure 4.11** and **Figure 4.12**). Specimens in series B were magnetized by continuous pulse of magnetizing field for 1.6 seconds with/without inversion mode. Specimens in series C were magnetized by continuous pulse for 0.6 seconds (with inversion mode) while varying the magnetizing direction.

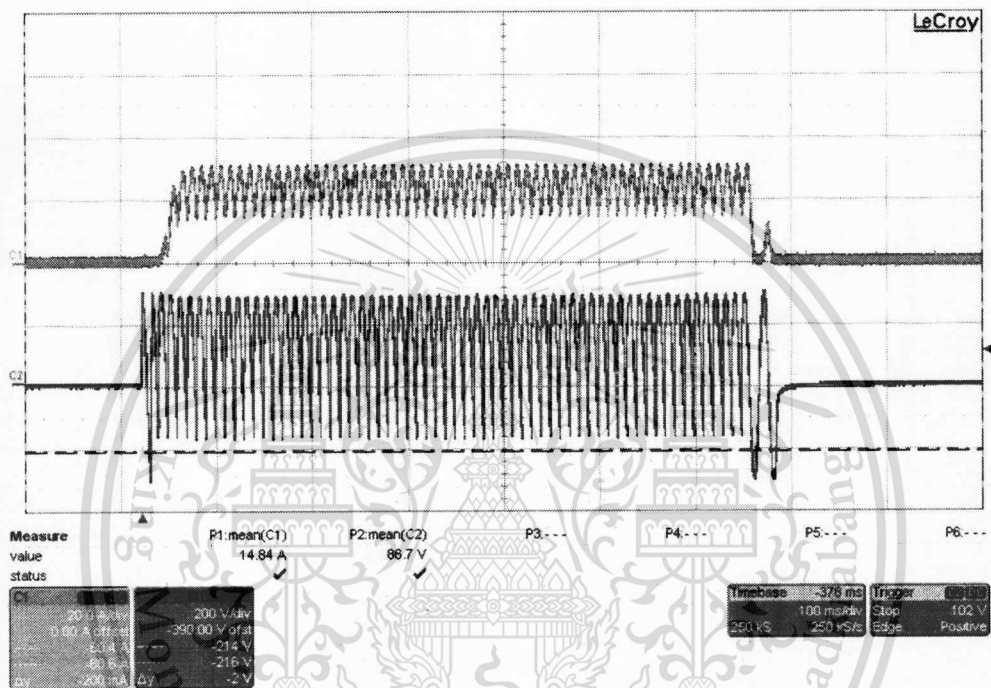


Figure 4.11 Magnetizing signal without inversion mode.

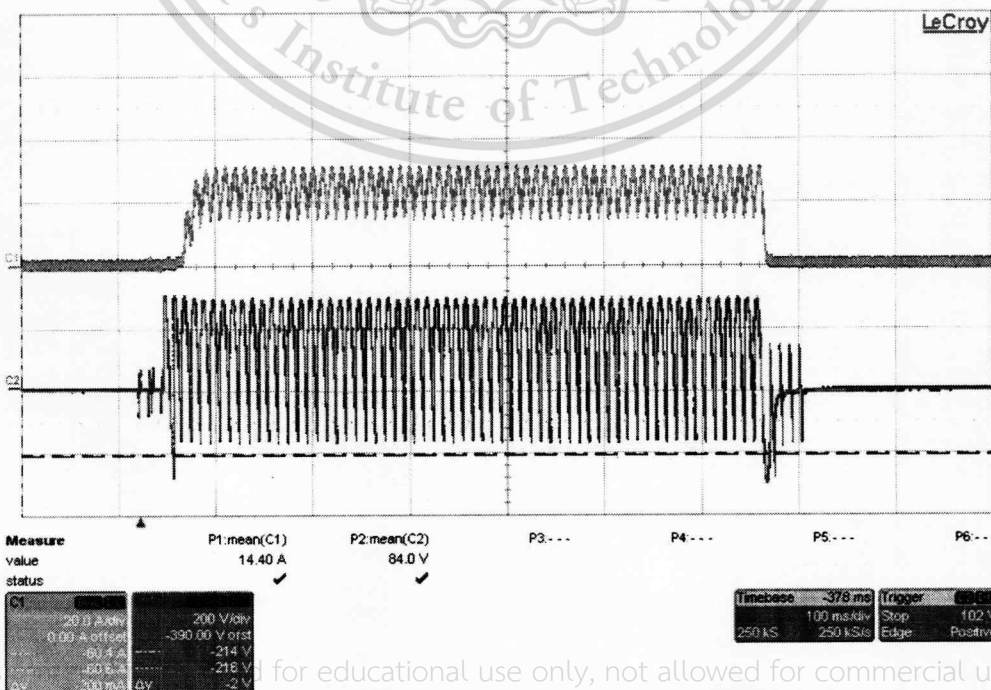


Figure 4.12 Magnetizing signal with inversion mode.

The magnetizer circuit operated without inversion mode, as shown in **Figure 4.11**, will suffer the back electromotive force. The current will rise again, and consequently reduce a remanence of permanent magnet. The pro of the invented magnetizer, presented in **Figure 4.12**, is that it can decay the current to zero in a short time while operating with the additional inversion mode.

As prescribed in **Chapter 2**, many researches have done in capacitor discharge magnetizer. The current signals of those researches are similarly to the current signal with inversion mode but the current decay time would take more than the invented magnetizer. Results, conducted by Ferahani and Razi [4], Lee [5], Wallace *et.al.* [26] and Sriveni *et.al.* [31] showed that the current decay time were 8 ms, 10 ms, over 20 ms and 12 ms respectively. On the contrary, the phase controlled magnetizer took only 3 ms to decay the current to zero. These results can be explained by natural response theory.

Ferahani and Razi [4] used an iron core structure of magnetic fixture which limited the magnetic field applied through specimen because the steel core structure had a saturation value of magnetic flux. This magnetic circuit is similar to the electric circuit (see **Table 2.2**). The conductor has a limitation of conducted flux or current. Ferahani and Razi also showed the same results as ours when varying the air gap. By decreasing the air gap, the inductance of coil will increase. The magnetic field intensity increased from 346835 AT/m to 538087 AT/m, and the magnetic flux density increased from 1.359 T to 1.595 T [4].

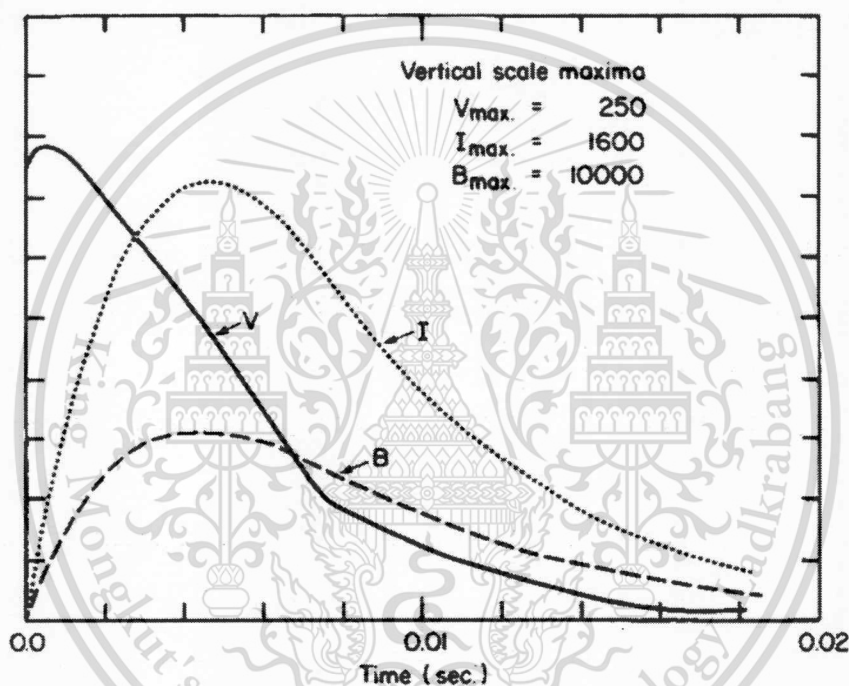
Lee's experiment [5] used a simple air-core solenoid that resulted in a magnetic flux density of 1 T. The magnetizing current had a decay time of 10 ms (see **Figure 4.13**). When comparing Lee's results to the invented magnetizer, the magnetic flux density had almost the same range of value, but the phase-controlled magnetizer had an advantage of shortening the current decay time, compared to the capacitor-type magnetizer.

Wallace *et.al.* [26] used the conductor screen (copper plate) to surround the magnet in order to concentrate the energy of the air gap into the magnet. The magnetizer is basically a transformer core with a large air gap. The result showed the flux density of 0.88 T in the air gap at a direct current of 10 A. However, the magnetizing field in the magnet had reached 3.8 T. Wallace *et.al.* concluded that the screen enabled the maximum energy, transferred from the capacitor-bank to the permanent magnets [26]. In addition, the current decay time had a very large value (over 20 ms), when comparing to the invented magnetizer, because the current decay time was depended on the time constant of RLC circuit.



Sriveni *et.al.* [31] used capacitor-type magnetizer to conduct an experiment. The results didn't mention the value of magnetic flux density but reported only voltage and current. Hence, there was no fly wheel diode in the magnetizer circuit, the voltage and current reversed its signs in discharge state. The figure of output current showed that it took 12 ms to decay this current to zero.

The capacitor-type magnetizer given in [4], [5], [26] and [31] are an RLC circuit. Current in a function of time was controlled by damping factor. In general, the signal of voltage and current may look like the figure illustrated in **Figure 4.13**.



**Figure 4.13** Capacitor-discharge circuit response [5].

At the under damped state, the current oscillates, surging back and forth between the capacitor and inductance. The peak current amplitude decreases with each swing because energy dissipates as heat due to the resistor. This behavior would be highly undesirable in a magnetizer, since even a relatively small reversal of current could demagnetize some of the material in the reverse direction [31].



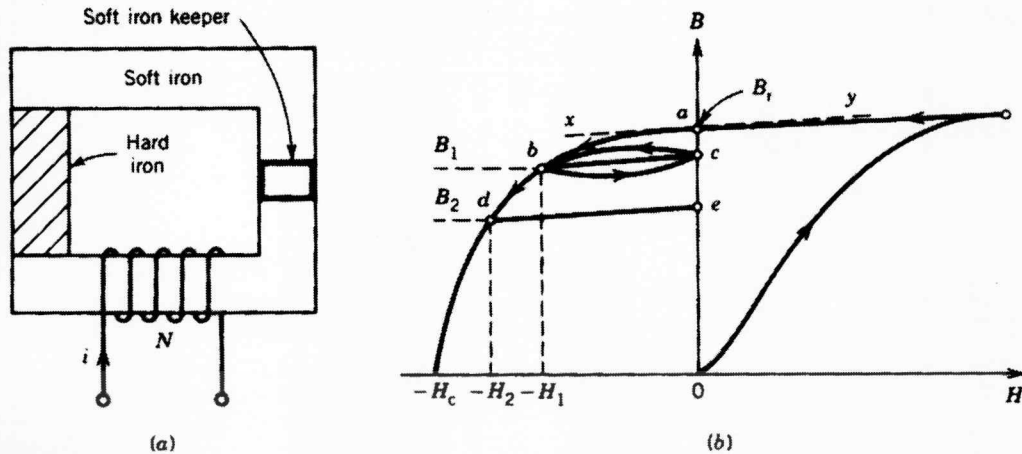


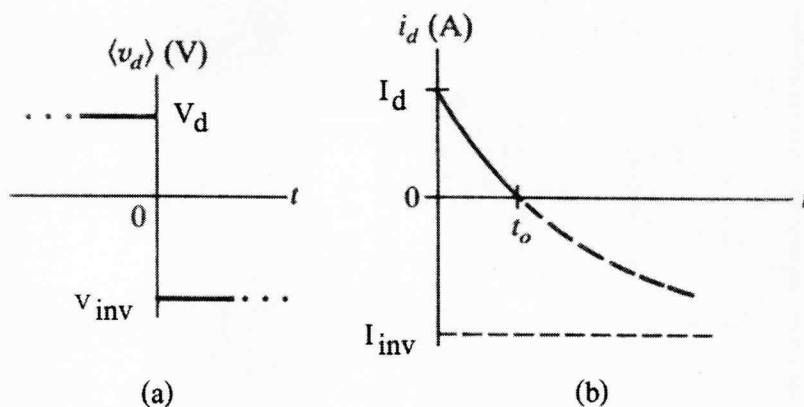
Figure 4.14 Permanent magnet system and its  $B$ - $H$  locus [10].

The magnetic circuit is shown in **Figure 4.14a**. Assume that the magnet material is initially unmagnetized. A large mmf is applied, and on its removal the flux density will remain at the residual value  $B_r$  on the magnetization curve, point  $a$  in **Figure 4.14b**. If a reversed magnetic field intensity of magnitude  $H_1$  is now applied to the hard iron, and the operating point moves to point  $b$ . If  $H_1$  is removed and reapplied, the  $B$ - $H$  locus follows a minor loop as shown in **Figure 4.14b**. The minor loop is narrow and for all practical purposes can be represented by the straight line  $bc$ , known as the recoil line. This line is almost parallel to the tangent  $xay$  to the demagnetizing curve at point  $a$ .

As long as the reversed magnetic field intensity does not exceed  $H_1$ , the magnet can be considered reasonably as permanent. If a negative magnetic field intensity greater than  $H_1$  is applied, such as  $H_2$ , the flux density of the permanent magnet will be decreased to the value  $B_2$ . If  $H_2$  is removed, the operation will move along a new recoil line  $de$  [10].

The natural response of phase controlled magnetizer and capacitor-type magnetizer are related to the time constant of magnetizer circuit. However, the control unit of invented magnetizer can take an advantage of this by controlling in the inversion region (after being magnetized). It is possible to control the voltage to have a maximum negative value  $V_{inv}$  as shown in **Figure 4.15**. The current decay time is depended on the difference between initial value ( $I_d$ ) and negative step ( $I_{inv}$ ). This can be explained by following equation:

$$t_0 = \left(\frac{L}{R}\right) \ln \left(\frac{I_d - I_{inv}}{|I_{inv}|}\right) \quad (4.4)$$



**Figure 4.15** Step response of R-L circuit [9].

The invented magnetizer was forced to decay a current to zero in short time by operating the firing angle at the maximum value in the inversion region. But other researches allowed the current to decay by natural response of the magnetizer circuit. Therefore, based on the results above, we can conclude that the invented magnetizer had an advantage of short current decay time.

According to the graph shown in **Figure 4.16**, the remanence of specimen series A magnetized for 0.6 seconds by the input of 8 T, 12 T and 15 T, had an inversion mode and no inversion mode. A set of three specimens were magnetized, measured its remanence, and averaged. The results showed a higher remanence from specimens which had the additional inversion mode. The remanence increased sharply from input 8 T to 12 T but slightly increased from input 12 T to 15 T. At each input of magnetizing field demonstrated that the inversion mode had an advantage of providing the remanence of 1 mT, which was higher than those without the inversion mode.

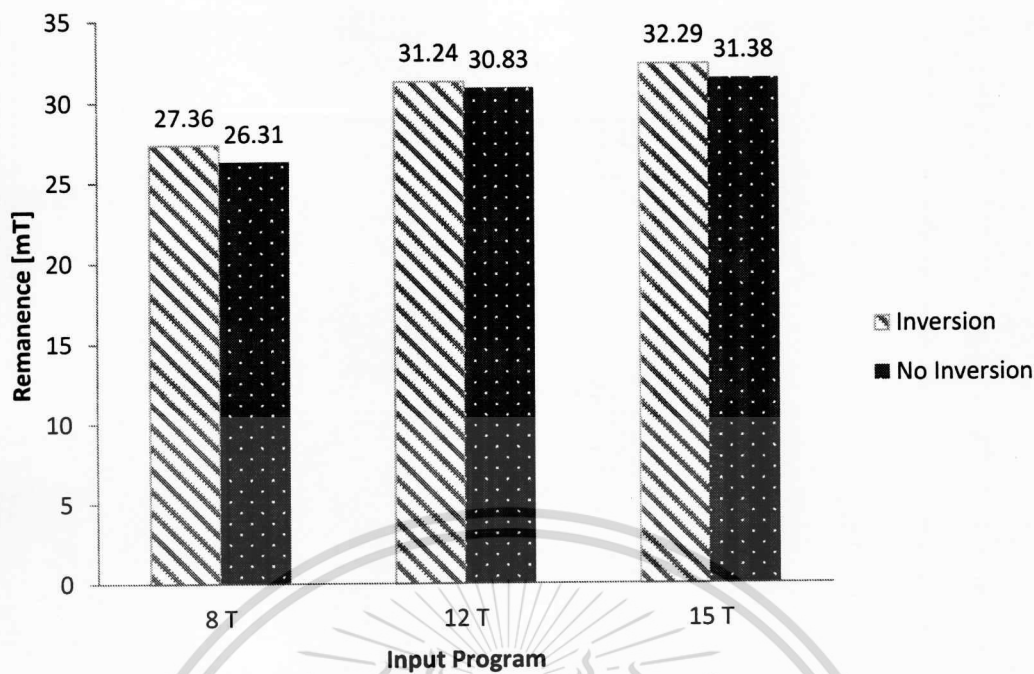


Figure 4.16 Average remanence of specimen series A (0.6 s).

The remanence of specimen series B, presented in Figure 4.17, magnetized for 1.6 seconds by the input 8 T, 12 T and 15 T, displayed a sharply increase from input 8 T to 12 T. However, it showed a slightly increase from input 12 T to 15 T. At each input of magnetizing field demonstrated that the inversion mode had an advantage of providing the remanence of 1 mT, which was higher than those without inversion mode.

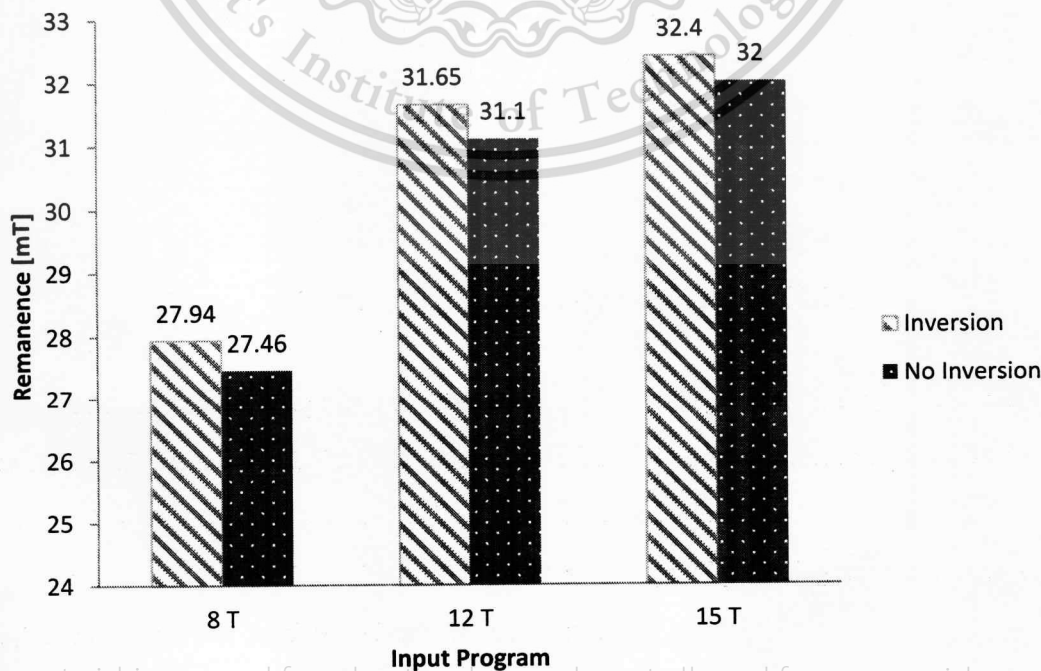
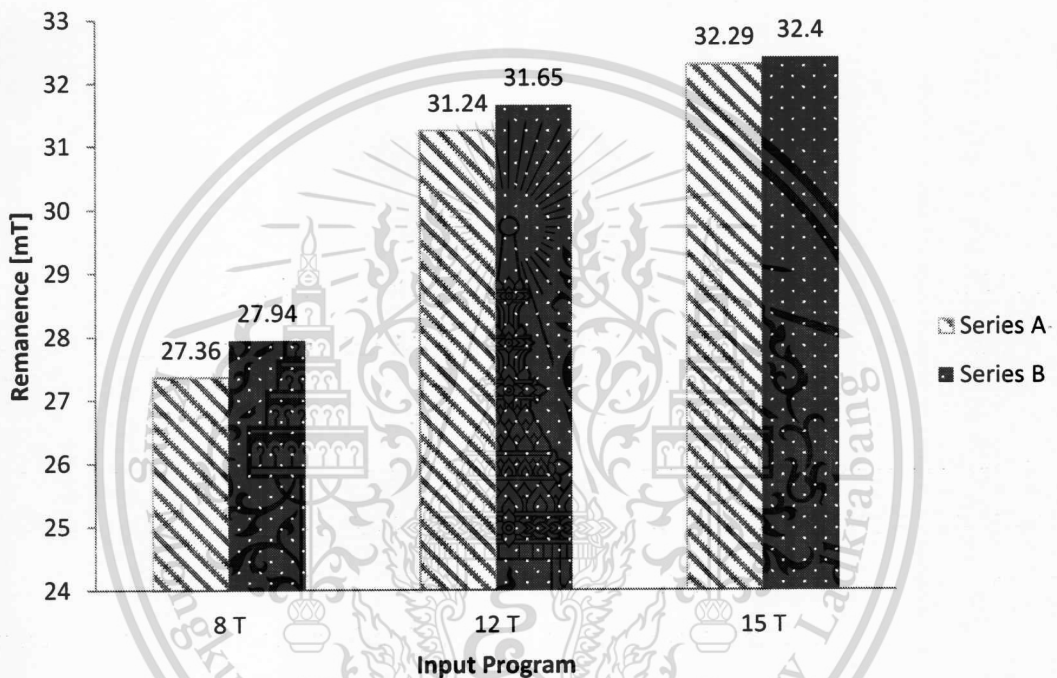


Figure 4.17 Average remanence of specimen series B (1.6 s).

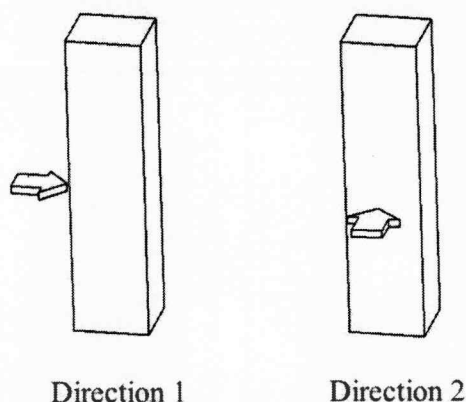


The remanence of series A, compared to those of series B, magnetized by input 8 T, 12 T and 15 T (following with an inversion mode), is shown in **Figure 4.18**. It seemed that the remanence of series B was higher than series A due to the longer duration of magnetizing field. The remanence sharply increased from input 8 T to 12 T but slightly increased from input 12 T to 15 T. At each input of magnetizing field demonstrated that the longer duration of magnetizing field, the remanence would increase averagely by 0.4 mT. Moreover, the remanence would be higher significantly when the input value was smaller.



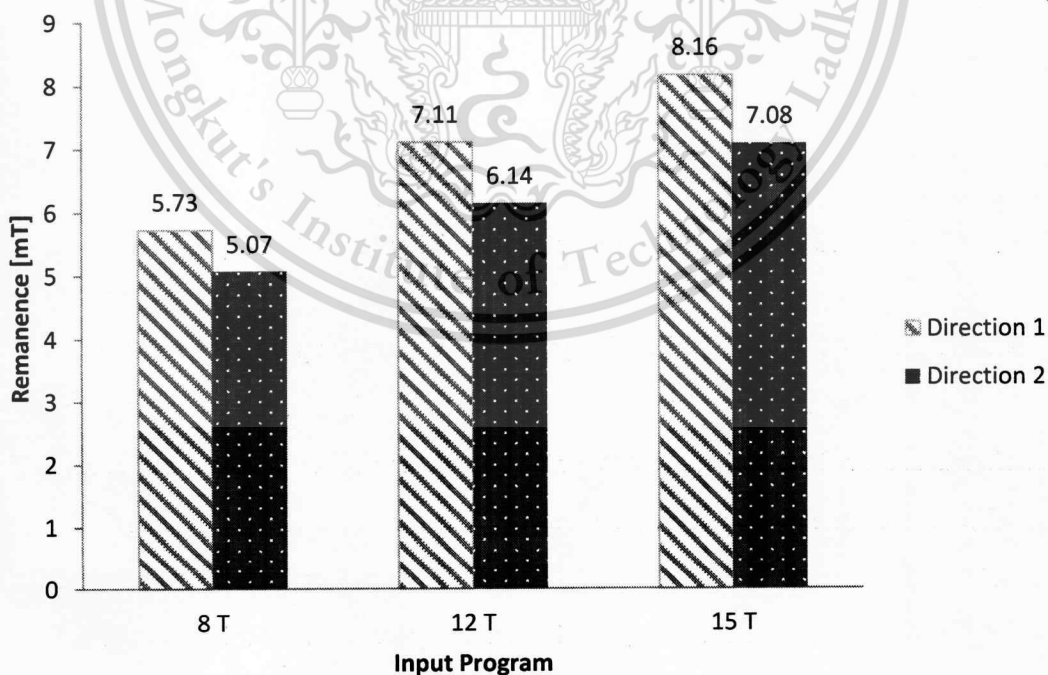
**Figure 4.18** Average remanence of specimen series A compare to B (have inversion mode).

Specimens in series C were magnetized by continuous pulse for 0.6 seconds (following with an inversion mode), by varying the magnetizing direction, as shown in **Figure 4.19**. Direction 1 was parallel to the compaction axis that was perpendicular to direction 2 (at the top plane). Note that the dimension of specimens had a width of 10 mm and a length of 9 mm, as shown in **Figure 3.8**.



**Figure 4.19** Magnetizing direction for specimen series C.

The remanence of specimen series C, magnetized in direction 1 and direction 2, is shown in **Figure 4.20**. The manufacturer said that the compaction powder could be magnetized in all directions and the result confirmed that by being magnetized in direction 1 and direction 2, this could give the same value of remanence. However, the results of remanence were different seeing that the width of direction 1 was about 1 mm smaller than that of direction 2. The remanence constantly increased from input 8 T to 15 T as a linear function.

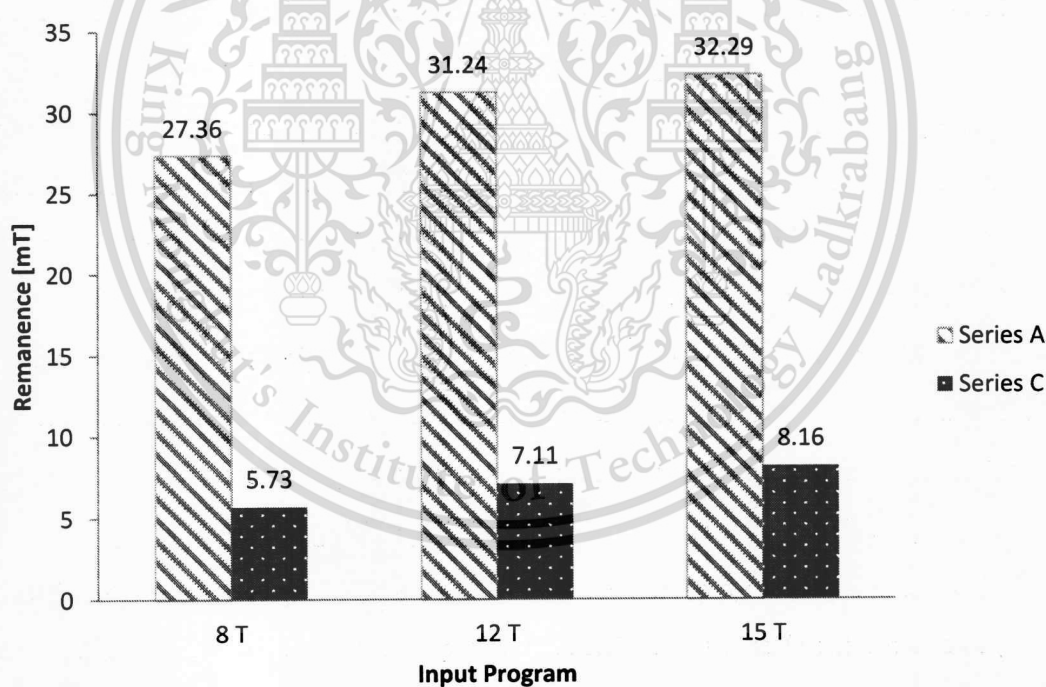


**Figure 4.20** Average remanence of specimen series C.

The average remanence of specimen series A compared to C is shown in **Figure 4.21**. The remanence constantly increased from input 8 T to 15 T as a linear function. At each input of



magnetizing field demonstrated that series A (with 1.7 mm width) had a remanence 4 times greater than series C (with 9 mm width), and it seemed to be higher when decreasing the input value. Thus, the remanence of specimens in series A was higher than in series C because of the difference in its thickness. Specimens in series A had a 1.7 mm of thickness but specimens in series C had a 9 mm of thickness. In contrast, when calculating the ratio of remanence of specimens in series A/specimens in series C, it appeared that at input 8 T had the highest ratio. And the ratio decreased when increasing the input of flux density into the program. This can be explained by the relationship between the change of air gap width and the inductance of magnetic fixture. The inductance will increase when decreasing air gap width. So, the experimental inductance for specimens in series A was higher than those in series C. Consequently, the magnetizing field applied to specimens in series A was also higher than the magnetizing field for specimens in series C (with the same program input condition). This would result in the higher remanence of specimens in series A than specimens in series C.



**Figure 4.21** Average remanence of specimen series A compare to C.

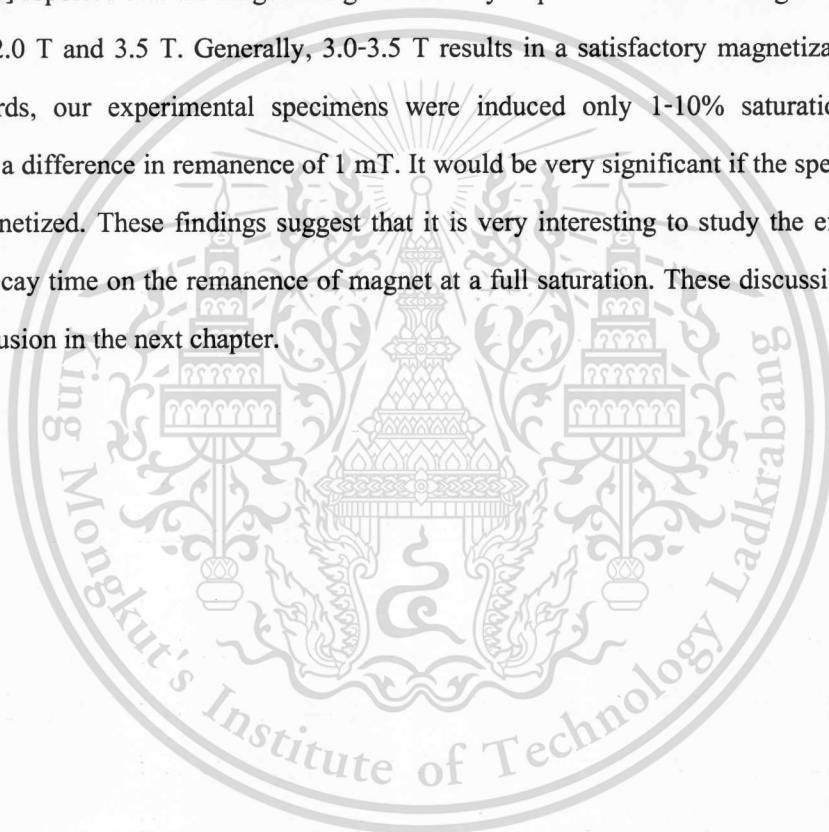
The results in series A showed that the remanence of permanent magnet increased as the input program increased. The inversion region plays an important role to block the effect of induced emf. This can be explained by Faraday’s Law (see **Section 2.5.5.1**). Faraday concluded that an electric current can be induced in a circuit by a changing magnetic field. Sriveni [31] discussed that it was possible that a rising current, as shown in **Figure 4.11**, could reduce the



remanence of magnet. He also reported that even a relatively small reversal of current could demagnetize some of the material in the reverse direction.

When comparing the results of series A to series B, it seemed that the longer duration of magnetizing field had a little advantage of remanence. Also, when comparing the results of series A to series C, it seemed that the narrow width had an advantage of remanence because its magnetic induction was much higher than wider width gap [4].

Since the magnetic flux density of invented magnetizer was stuck at the saturation of core (1.8 T), these experiments were only a small part of the study of magnetization effects. Chang [34] reported that the magnetizing flux density required for NdFeB magnets had a range between 2.0 T and 3.5 T. Generally, 3.0-3.5 T results in a satisfactory magnetization [34]. In other words, our experimental specimens were induced only 1-10% saturation and they presented a difference in remanence of 1 mT. It would be very significant if the specimens were fully magnetized. These findings suggest that it is very interesting to study the effects of fast current decay time on the remanence of magnet at a full saturation. These discussions will lead to a conclusion in the next chapter.



## CHAPTER 5

# CONCLUSION

### 5.1 Conclusion

It was anticipated that SCR-type magnetizer would have an advantage over the capacitor-type magnetizer. The theory led us to infer that the magnetizing field with inversion mode would give better permanent magnet properties. The phase controlled magnetizer has been invented and improved. Design and construction of the invented magnetizer were described. The maximum flux density at the air gap can reach 1.5 T. It seems that the maximum flux density cannot be measured due to limitation of equipment. The output voltage and current of magnetizer, driven into magnetic fixture, were related to the firing angle.

The magnetic flux density of the designed magnetic fixture could reach the maximum value (at the core, 1.8 T), which was transferred to the specimen. However, this was a limitation of a core model. This finding suggests that to magnetize neodymium magnet, it is better to design an air core that can give the higher magnetic flux density than this model. The magnetizing flux density, required for NdFeB magnets in general 3.0-3.5 T, results in a satisfactory magnetization. But a small hysteresis loop can be acquired. These specimens were induced only 1-10% saturation and they presented a difference of 1 mT. It would be very significant if the specimens were fully magnetized. These findings suggest that it is very interesting to study the effects of fast current decay time to the remanence of magnet at a full saturation. This experiment also implied that the temperature rising due to the high current passing through the conductor coil was significant. Further improvement of current should also concern about this effect.

Microcontroller is very useful and flexible. With 40-pin input/output, it is easy to add or manage the input/output devices. The experiments showed that microcontroller could operate precisely as the program flowchart. The improvement of ac load line gave a change to peak voltage value, which was a constant variable used in program, so the program code needed to be re-generated. At present, the program cannot fully auto-operate due to the limitation of ROM. This finding suggests that the microcontroller should have more ROM for fully auto-operate program code for the future improvement.

The magnetizer performances e.g. firing angle, voltage, current and magnetic flux density, were investigated. These results indicated that the delay in firing angle was significantly

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related to the voltage, input to interrupt pin. Consequently, the rate of rising voltage is necessary to be taken into account. The delay of firing angle reduced to 8 degrees when another transformer 24V was applied as an input to the interrupt pin. The output voltage and current from phase-controlled magnetizer were in agreement with program calculation. The results also illustrated that the firing angle in the range of 60-90 degree showed discontinuous current signal. This finding suggests that the magnetic fixture should concern about the time constant of magnetic fixture, which relates to the inductance of coil, for further improvement. During the inspection of magnetic flux density, it was found that the actual value of magnetic flux density applied to specimen could not be measured. This finding suggests further improvement for the core magnetic fixture that it should add the soft iron keeper that can be utilized to measure the flux density in core at that state.

The results of magnetic flux density confirmed that this designed magnetizer had an advantage of low current. The flux density of 1 T can be obtained with a relatively low current of 28 A. This experiment also indicates that the air gap is significantly related to the magnetic induction. The narrower of the gap width provides the higher magnetic induction.

As explained earlier, many research have done in capacitor discharge magnetizer. The results showed that the current decay time in capacitor discharge magnetizer took longer duration than in the invented magnetizer, which took only 3 ms to decay the current to zero. In addition, the results from specimens in series A and series B confirmed that the phase-controlled magnetizer provided higher remanence for specimens, which had the additional inversion mode. It appeared that the remanence had a relationship with the magnetic flux density. It is concluded that remanence is a linear function of magnetic flux density between the range of 0-2.0 T. These findings suggest that further improvement of magnetic flux density of the invented magnetizer should cover the saturation point for neodymium magnet.

Specimens in series B had a higher remanence than specimens in series A due to the longer duration in magnetizing field. The results of specimens in series C indicated that the remanence constantly increased from input 8 T to 15 T as a linear function, and the direction was not significantly related to the remanence. Specimen in series A had a higher remanence than specimens in series C. It appeared that the narrow width gap had higher remanence because the magnetic induction value is much higher.



## 5.2 Suggestion

This work had conducted the experiment at a low value of magnetizing field. Therefore, there are not adequate data to conclude that the additional inversion mode has an advantage over the natural response. Future works should conduct at an exceeded value of magnetizing field.



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