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# Ferromagnetic Materials Characteristics: Their Application in Magnetic Coresdesign Using Hysteresis Loop Measurements

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***ABSTRACTS:****The paper analyzedferromagnetic materials characteristics and their applications for the design of magnetic coresusing hysteresis loop measurements. This is aimed at determining the suitability of ferromagnetic material for the design of magnetic cores use in electrical apparatus in terms of magnetic flux density$B_r$, magnetizing force$H_c$., remanent flux, and coercive force.*

*Laboratory experiment tests set-up of four ferromagnetic materials configurations viz: cobalt steel, cast steel, Silicon ironand 78.5 Permalloy were conducted. Set of devices and software tools using primary injection test equipment ISA T2000 model with oscilloscope feature and a measured frequency of 100 Hz were used to carry out measurement of these materials and capture the magnetic hysteresis loop of the core materials.*

*Results show that Cobalt Steel is a hard magnetic material with high residual flux, large coercive force and large hysteresis losses. It is suitable for making permanent magnets. Cast steel material has high permeability and fairly good coercivity, hence suitable for design of electromagnets cores. Silicon iron and Permalloy materials are soft magnetic materials. They offer unique combination ofhigh permeability,high saturation flux density, low coercive force and remanent flux density, which means low hysteresis losses. Silicon iron is most suited for making armature and transformer cores which are subjected to rapid reversals of magnetization.WhilePermalloymaterial is suitable for the designof high frequency direct current inductor. The shape of the B-H curve indicates how relative permeability of the material changes along with the magnetic flux density and magnetizing force.*

***KEYWORDS:****Ferromagnetic materials, Hysteresis loop, Magnetic core, Permeability, Flux density, Magnetizing force, Coercive force and Remanent flux.*

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## I. INTRODUCTION

The magnetic material is the paramount player in the design of magnetic components. The important class of magnetic materials is the ferromagnetic materialssuch asCobalt Steel, Cast Steel, Silicon ironand 78.5 Permalloy or their compounds.These materials and their alloys have high permeability, sometimes ranging into hundreds of thousands. In addition to its high permeability, the advantages of the magnetic core are that the magnetic path length (MPL) is well-defined, and the flux is essentially confined to the core, except in the immediate vicinity of the winding. The susceptibilities of ferromagnetic materials are typically of order $+10^3$ or $10^4$ or even greater. The ferromagnetic susceptibility of a material is quite temperature sensitive, and, above a temperature known as the Curie temperatureof the other of 1400 K.The magnetization curves for ferromagnetic materials are all strongly dependent upon purity, heat treatment and other factors [1] –[4]. The nonlinearity of permeability material are plotted with the quantity of field intensity (H), on the horizontal axis of the graph and on the vertical axis, is place the quantity of flux density (B). These set of curves are called magnetization curves. The fundamental purpose of any magnetic core is to provide an easy path for flux in order to facilitate flux linkage, or coupling, between two or more magnetic elements[5][6].

Ferromagnetic materials have a large, positive susceptibility to an external magnetic field. They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed. Ferromagnetic materials have some unpaired electrons, so their atoms have a net magnetic moment. They get their strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atom's moments ($10^{12}$ to $10^{15}$) are aligned parallel so that the magnetic force within the domain is strong [7]. When a ferromagnetic material is in the un-magnetized state, the domains are nearly randomly organized and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part. Iron, nickel, and cobalt are examples of ferromagnetic materials. Components with these materials are commonly inspected using the magnetic particle method[7]-[10].

## II. DESCRIPTION

Ferromagnetic materials properties are found in certain forms of iron and its alloys with cobalt, tungsten, nickel, aluminum, and other metals. Ferromagnetic materials are characterized by the following attributes:

a) They can be magnetized much more easily than other materials;
b) They have high intrinsic saturation (maximum) flux density Bmax;
c) They are magnetized with widely different degrees of ease for different values of magnetizing force;
d) They retain magnetization when the magnetizing force is removed; and
e) They tend to oppose a reversal of magnetization after once being magnetized [1].

According to EL-Saadany, [9] the magneto-motive force (mmf) is the ability of a coil to produce magnetic flux. The mmf unit is Amp-turn and is given by

$$mmf = NI \quad (AT) \qquad (1)$$

The magnetic field strength $H$ is the mmf per unit length along the path of the flux. When current flows in a conductor, it is always accompanied by a magnetic field. The strength, of this field is proportional to the amount of current and inversely proportional to the distance from the conductor called Magnetic field strength H, and is expressed as

$$H = \frac{mmf}{l} \quad AT/m \quad (2)$$

Where $l$ is the mean path length of the magnetic flux in meter

Hence the flux density in a magnetic medium, due to the existence of a magnetizing force, depends on $mmf = \Re\Phi$, where the reluctance is given by

$$\Re = \frac{l}{\mu A} (3)$$

where $l$ = the average length of the magnetic core (m), A = the cross section area ($m^2$), and $\mu$ = The permeability of the material ($AT/m^2$)

In magnetics, permeability is the ability of a material to conduct flux and different materials have different permeability [1]. Also, in electromagnetism, permeability ($\mu$) is the measure of the ability of a material to support the formation of a magnetic flux within itself [7].

The permeability of a magnetic material is a measure of the ease in magnetizing the material. Permeability,$\mu$ is the ratio of the flux density, B, to the magnetizing force, H.

that is $\mu = {}^{B}/_{H}$(4)

The permeability of the material is given by $\mu = \mu_o \mu_r$(5)

Where $\mu_o$ = the permeability of air and $\mu_r$ = the relative permeability.

The relationship between B and H is not linear, as shown in the hysteresis loop in Figure 1. Then, it is evident that the ratio, B/H, also varies. The magnitude of the permeability at a given induction is the measure of the ease with which a core material can be magnetized to that induction.

From the above relationships, it can be concluded that the magnetic flux density $B$, is expressed as

$$B = \frac{\Phi}{A} = \frac{mmf\ /\Re}{A} = \frac{(Hl)/(l/\mu A)}{A} = \mu H \mathrm{Wb/m^2} \quad (6)$$

Where $\Phi$ is the magnetic flux,

Thus, the flux density $B = \mu_o \mu_r H$. (7)

thepermeability of the medium and the intensity of the magnetic field. The maximum permeability is the point where the slope of the B/H curve for the un-magnetized material is the greatest. For ferromagnetic materials the permeability is not constant but varies with flux density.The nonlinearity of permeability material are plotted with the quantity of field intensity (H), on the horizontal axis of the graph and on the vertical axis, is place the quantity of flux density (B).

### 2.1CORE LOSSES

There are two types of energy losses that are present in the core made of ferromagnetic materials. These are hysteresis losses and eddy current losses [4].

***a) Hysteresis Loss***

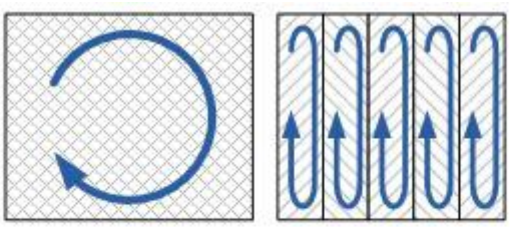
Transformers and rotating machines operate on alternating currents, in such devices, the flux in the iron changes continuously both in value and direction. The core of a transformer is subjected to an alternating magnetizing force and for each cycle of emf a hysteresis loop is traced out. It is known as hysteresis loss [10]. The magnetic domains are therefore, oriented first in one direction, then in another direction, at a rate that depends upon the frequency. The magnetic material absorbs energy during each cycle and this energy is dissipated as heat. The amount of heat released per cycle is equal to the area of the hysteresis loop. In other words,the enclosed area within the hysteresis loop is a measure of the energy lost in the core material during that cycle. The hysteresis losses can be reduces using a magnetic material with narrow hysteresis loop [11].
The hysteresis losses can be calculated using an empirical formula given in equation (8) as

$$P_h = K_h x \text{ V } x f x B_{max}^n \qquad (8)$$

Where$P_h$ =Hysteresis losses (Watt), $K_h$ = Hysteresis constant,V = The material volume,$f$ =Excitation frequency,$B_{max}$ = Maximum flux density, and$n$ = Material constant (1.5-2.5).

***b) Eddy Current Loss***

Eddy current loss takes place when a coil is wrapped around a core and alternating ac supply is applied to it. As the supply to the coil is alternating, the flux produced in the coil is also alternating. By faradays law of electromagnetic induction, the change in flux through the core causes emf induction inside the core. Due to induction of emf eddy current starts to flow in the core. The result of eddy currents is to heat up the core and lost in the form of heat energy resulting in $I^2R$ losses.The eddy current loss is caused when the lines of flux pass through the core, inducing electrical currents in it. These currents are called eddy currents and produce heat in the core. Eddy currents losses can be reduce by splitting the core into more units along its length as shown in Figure 1, taking care to insulate the sections from each other, the amount of current which flows get reduced and hence the eddy current losses decrease progressively. The voltage induced in each section is one half of what it was before, with the result of the Eddy current, and the corresponding losses are considerably reduced [4] [12] [13].



(a) (b)

**Figure 1: (a) Solid core, (b) Laminated core.**

The Eddy current losses can be calculated using an empirical formula in equation (9) as

$$P_e = K_e \text{ x V x } (f x t x B_{max})^2 \qquad (9)$$

Where$P_e$ = Eddy current losses (in Watt), $K_e$= material dependent constant, V = material volume, $f$ =excitation frequency, $t$ =lamination thickness, and$B_{max}$ = maximum flux density.

## III. MAGNETIC MATERIALS CHARACTERISTICS AND METHODS

***3.1 Determination of the Magnetic Hysteresis loop***

The fourselected important class of Ferro-magneticmaterials areCobalt Steel, Cast Steel, Silicon ironand 78.5 Permalloyor their compounds. Laboratory experiment tests of these different types offerromagnetic materials configurations mentioned above were investigated. A set of devices and software tools using primary injection test equipment (ISA T2000) model with oscilloscope feature and a measured frequency of 100 Hz were used to carry out measurement of the CTs core materials and to examine the transient behavior.Figure 2 shows the schematic diagram of hysteresis test set-up of steel close-core CT. In the measurement setup, the oscilloscope feature was utilized to trace and capture the magnetic hysteresis loop of the CT core.

***3.2 Experimental Procedureof Hysteresis Loop Measurement***

Before starting the measurement, the selected C400, 1200:5A current transformer magnetic core materials were totally demagnetizedand then subjected to gradually increasing magnetizing force, while the flux density was plotted. The slope of these curves, at any given point gives the permeability at that point. Permeability is not constant; therefore, its value can be stated only at a given value of B or H.

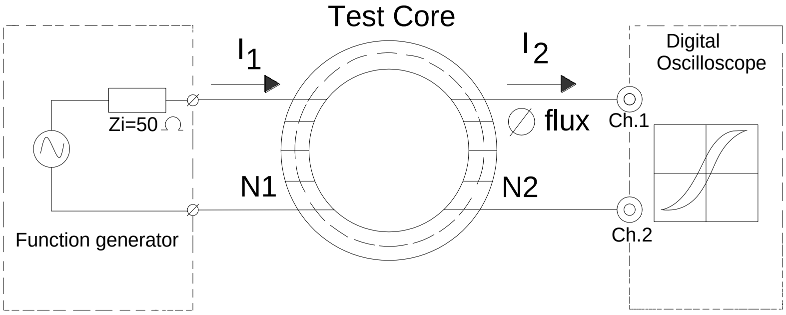



**Figure 2: Hysteresis loop test set-up of steel closed-core CT.**

The current transformers cores were de-magnetizing to remove the remanent flux in the core. This was accomplished by applying a suitable variable alternating voltage to the secondary, with initial magnitude sufficient to force the flux density above the saturation point, and then decreasing the applied voltage slowly and continuously to zero.This was performed so as to put the magnetic field strength and the flux density at zero point on the magnetization curve.
Figure 3 (a & b) shows a toroidal sheet steel core CT and its equivalent magnetic circuit.

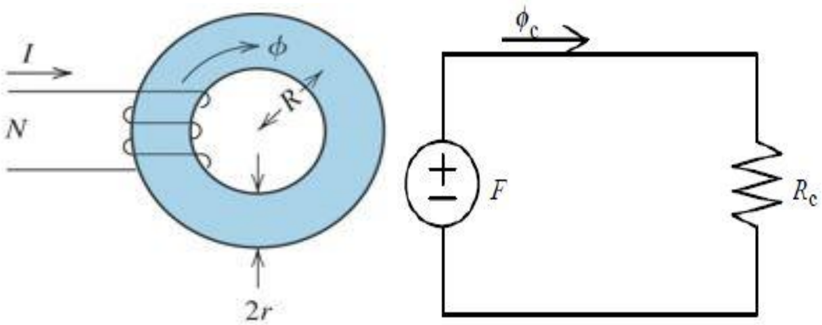



**Figure 3: (a) A Toroid close steel magnetic core CT (b) Equivalent magnetic circuit**

Drawing the B-H curve we generally take horizontal axis as magnetizing force H, and vertical axis as flux density B. The magnetic hysteresis loop of a magnetic material represents the relationship between its magnetic flux density $B_r$as a function of the magnetic field intensity$H_c$. Figure 4 shown families of four different ferromagnetic materials namely Cobalt steel, Cast steel, Silicon iron andPermalloy hysteresis loops measurements. When magnetic flux density is plotted against the magnetizing force, the resulting set of loops or (curves) are called B-H curves; indicating their residual flux *Br* and coercive force $-Hc$ respectively. The outer loops represent that of cobalt steel, followed by cast steel, silicon iron and the inner loop represents that of 78.5 Permalloy materials respectively. These set of magnetization curves, represents the relationship between flux density (B) and magnetic field intensity (H) for soft-iron magnetic cores. The characteristics tabulated in Table 1 for the magnetically soft and hard materials are the maximum intrinsic flux density *Bmax*, residual flux density *Br*, relative permeability $\mu_r$and the coercive force *Hc* respectively. The enclosed area is a measure of energy lost in the core material during that cycle [1][13].

**Table 1: Properties of Ferromagnetic Materials**

| S/N | Materials | Elements | Composition per 100 | Maximum Flux density ($B_{max}$) | Relative Permeability ($\mu_r$) | Residual Flux Density ($B_r$) | Coercive Force ($H_c$) |
|---|---|---|---|---|---|---|---|
| 1 | Cobalt Steel | Fe, Co, C | 64, 35, 1 | 1.0 | 250 | 0.95 | 8.0 |
| 2 | Cast Steel | Fe, C | 60, 40 | 2.0 | 1000 | 0.85 | 5.0 |
| 3 | 78.5 Permalloy | Ni, Fe, Mn | 78.5, 20.9, 0.6 | 1.7 | 12K-100K | 0.6 | 0.05 |
| 4 | Silicon Steel | Fe, Si. | 95.5, 4.5 | 1.9 | 8300 | 0.5 | 0.5 |

Source: http://www.maxwells-equations.com/materials/permeability. Cited April 20, 2015.

It can be notice that the flux density increases in proportion to the field strength until it reaches a certain value were it cannot increase any more but becoming almost level and constant as the field strength continues to increase. The shapes of the hysteresis loops depend on the nature of the magnet material.

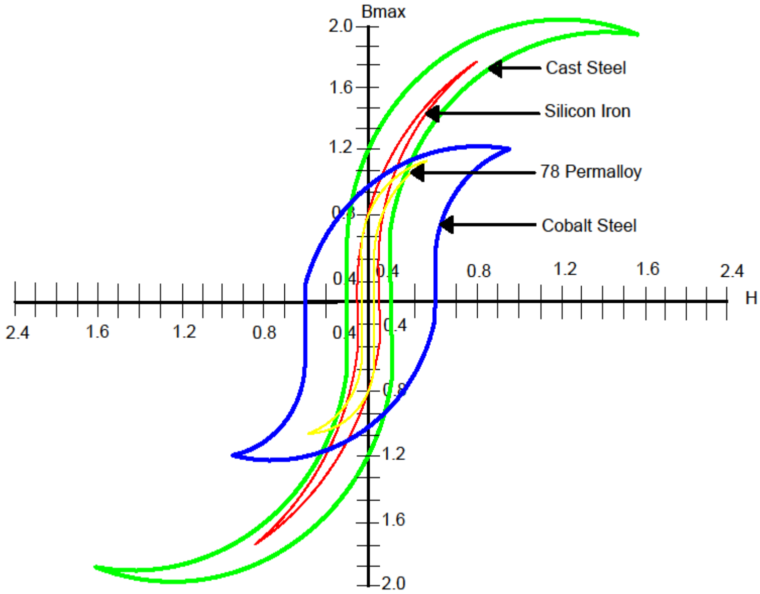



**Figure 4: Families ofFerromagnetic Materials hysteresis loops**

## IV. ANALYSIS AND RESULTS

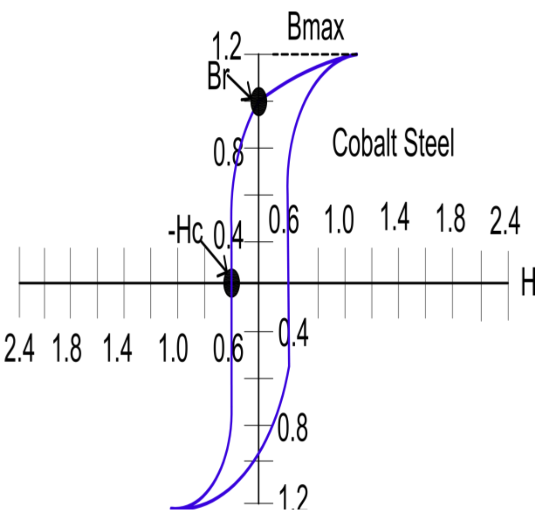
Starting with a neutral magnetic material traversing the B-H loop at the origin ‘0’; the magnetizing current is increased in a positive direction the magnetizing force $H$, increases along the dashed line to the saturation point, $Bmax$ while the magnetic flux density increases very slowly from the origin of the B-H point ‘0’ to point ‘a’andthereafter, the flux density increases proportionally with increasing $+H$. This portion of the curve is almost linear as it heads towards saturation region of the curve as shown inFigure 4.When the magnetizing current in the coil is reduced to zero, the magnetic field circulating around the core also reduces to zero. However, the magnetic flux does not return to zero due to the residual magnetism present within the core and this is shown on the curve from point ‘*Bmax’* to point *Br*.To reduce the remanent flux density Br to zero, a magnetizing force $-Hc$ must be applied in the direction opposite to that of the magnetizing force, *H*, formerly applied. This magnetizing force is called the coercive force. This coercive force reverses the magnetic field re-arranging the molecular magnets until the core becomes un-magnetized at point ‘$-Hc$’

An increase in this reverse current causes the core to be magnetized in the opposite direction and increasing this magnetization current further cause the core to reach its saturation point but in the opposite direction at point “d” on the curve. When the magnetizing current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse direction at point “e”. Further reversing the magnetizing current flowing through the coil into a positive direction causes the magnetic flux to reach zero, at point “f” on the curve and as before increasing the magnetization current further in a positive direction will cause the core to reach saturation at point “a” as shown in the Figure. Explaining the B-H curve, the flux moves successively from *+Bm, +Br, O, -Bm, -Br, O,* and *+Bm,* corresponding respectively to point‘a’, ‘b’, ‘c’, ‘d’, ‘e’, ‘f’, and back to point ‘a’. When the magnetic materials are taken through a complete cycle of magnetization and demagnetization, the results are as shown in Figure 4.

The shape of the B-H curve entirely depends upon the nature of the material not on the structure of material piece. The shape of the B-H indicates how relative permeability of the material changes along with the magnetic flux density and magnetizing force.

## V. RESULTS

The effect of magnetic hysteresis shows that the magnetization process of a ferromagnetic core and therefore the flux density depends on which part of the curve the ferromagnetic core is magnetized on as this depends upon the circuits past history giving the core a form of “memory”. Ferromagnetic materials remain magnetized after the external magnetic field has been removed.Figure 5 is for Cobalt Steel, a hard magnetic material. Due to its high retentivity and large coercive force, it is well suited for making permanent magnets. However, due to large hysteresis loss, it is not suitable for rapid reversals of magnetization. Figure 6 is for cast steel. It shows that this material has high permeability and fairly good coercivity, hence making it suitable for cores of electromagnets. Figures7 and 8loops represents Silicon iron and Permalloy materials respectively, bothloops shows high permeability and low hysteresis loss. However, Silicon iron is most suited for making armature and transformer cores which are subjected to rapid reversals of magnetization. 78.5 Permalloy offers a unique combination of high saturation flux density, and low coercive force (which means low core loss) making it suitable for designing high frequency dc inductors.



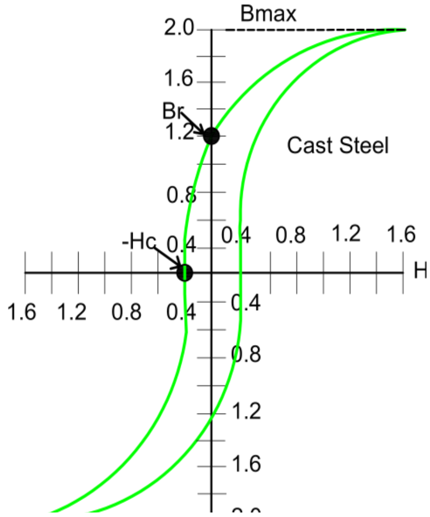
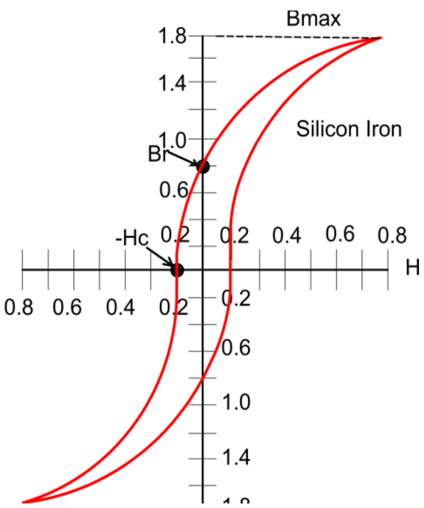




**Figure 5: Cobalt Steel hysteresis loopFigure 6: Cast Steel hysteresis loop.**

The magnetic properties and in particular the iron losses are sensitive to mechanical stress and the heat treatment used in the laminations. Of the materials available, silicon iron finds the most extensive use. Its permeability is large of all the ferromagnetic materials available. It revealed that soft ferromagnetic materials such as silicon iron have very narrow magnetic hysteresis loop resulting in very small amount of residual magnetism, low coercive force; high magnetic permeability making them ideal for use in relays, solenoids and transformers cores as they can easily be magnetized and demagnetized. It can be used in applications requiring high performance with minimum losses.



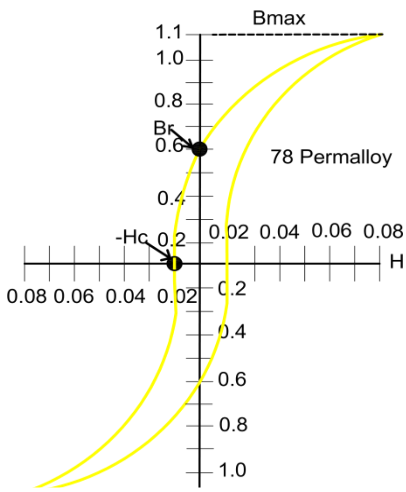




**Figure 7:Silicon iron hysteresis loopFigure 8:Permalloy hysteresis loop**

Comparing the properties of different ferromagnetic materialson the hysteresis loop in terms of (a) remanence flux, (b) residual flux density, (c) coercive force, and (d) coercivity; of these properties, two important quantities on the hysteresis loop are the residual flux density Br, and the coercive force Hc. The residual flux density is a measure of how much of the magnetic energy is retained by the material upon removal of the magnetic field. The higher the residual flux density, relative to the saturation level Bmax, the more of the applied magnetics energy is store in the material. The coercive force is related to the demagnetization of the material. The smaller is the coercivity, the closer this point is to the point of total demagnetization. Soft magnetic materials have low coercivity and take less energy to demagnetize. Conversely, hard magnetic materials have high coercivity and take more energy to demagnetize it.

Analyzing ferromagnetic materials using hysteresis loop measurements provides the following information
1. The shape and the size of the hysteresis loop depend on the nature of the material chosen.
2. Smaller hysteresis loop area symbolizes less hysteresis loss.
3. Provides the value of retentivity and coercivity of a material. Thus the way to choose perfect material to make permanent magnet, core of machines becomes easier.
4. Residual magnetism can be determined and thus selecting material for electromagnets applications become easy.

The use of silicon iron, for the design of current transformer core is proposed because of the following advantages:
a) High saturation flux density,
b) It is characterized by low coercivity and remanent flux density, which means low hysteresis losses.
c) Increased electrical resistivity, thus reducing the eddy current losses, and improved the material's stability with age.
d) High magnetic permeability at high flux density.

## VI. CONCLUSION

The paper analyzedferromagnetic materials characteristics and their applications for the design of magnetic cores using hysteresis loop measurements.It aimed at determining the most suitable magnetic material for designing magnetic cores of electrical apparatus in terms of magnetic flux density$B_r$, magnetic field intensity$H_c$., remanent flux, and coercive force parameters.Laboratory experiment tests set-up of four different ferromagnetic materials configurations were conducted and results presented. Soft magnetic materials have low coercivity and take less energy to demagnetize. Conversely, hard magnetic materials have high coercivity and take more energy to demagnetize it. The shape and the size of the hysteresis loop depend on the nature of the material chosen.Smaller hysteresis loop area symbolizes less hysteresis loss.

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