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# STUDY AND IMPROVEMENT OF PROPERTIES OF ELECTRICAL IRON FOR CURRENT TRANSFORMERS

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A thesis submitted Ammar Al-JANABI partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 25.11.2016 in Department of Physics.

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# TABLE OF CONTENTS

Page

# LIST OF SYMBOLS

| | |
|---|---|
| A | Cross sectional area of iron core |
| B | Magnetic flux density |
| CT | Current Transformer |
| Din | Inner diameter of iron core |
| $D_{out}$ | Outer diameter of iron core |
| d | Thickness of the lamination |
| dx | Sheet thickness |
| $E_p$ | Electromotive force of the primary coil |
| $E_S$ | Induced electromotive force for the secondary coil |
| e | Induced voltage |
| $f_m$ | Magnetizing frequency |
| H | Magnetic field intensity |
| $I_e$ | Induced current or exciting current |
| $I_{ns}$ | Nominal or rated secondary current |
| $I_P$ | Primary current |
| $I_S$ | Secondary current |
| $K_{nc}$ | Nominal or rated current ratio = Inp / Ins |
| $K_c$ | Current ratio |
| N | Number of turns |
| $P_{tot}$ | Total losses |
| $P_{edd}$ | The eddy current loss |
| $P_{hys}$ | The hysteresis loss |
| $P_{class}$ | Classical loss |
| W | Core width |
| $\beta$ | Phase angle = angle between Ip and Is reversed ;positive when Is leads on Ip Usually in cent radians |
| $\Phi$ | Magnetic flux |
| $\delta$ | Phase angle between $I_S$ and $E_S$ |
| $\alpha$ | Phase angle between $\phi$ and $I_e$ |
| $\mu$ | Permittivity |
| $\sigma$ | Electrical conductivity |
| $\rho$ | Electrical resistivity |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| CT | Current Transformer |
| CGO | Conventional grain oriented steel |
| DC | Direct Current |
| IEEE | Institute of Electrical and Electronics Engineers |
| Goss | Grain Oriented Silicon Steel |
| Goes | Grain Oriented Electrical Steel |
| PWM | Pulse width modulation |

# LIST OF FIGURES

Page

# LIST OF TABLES

Page

# ABSTRACT

## STUDY AND IMPROVEMENT OF PROPERTIES OF ELECTRICAL IRON OF CURRENT TRANSFORMERS

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Department of Physics

MSc. Thesis

Advisor: Assoc. Prof Taylan YETKIN

In this thesis we performed several different thermal and mechanical operations for current transformer production to study the behavior of current transformers (CTs) and change of their properties with respect to these preparation techniques. The CTs produced were subject of detailed measurements to identify optimum process and optimum operation of CT.

This thesis includes studying the magnetization curves for various samples of electrical iron that are used as cores in current transformers and the factors that most affect their quality to obtain the ideal heating treatment process such as varying the treatment time, temperature or the rate of cooling process.

Several samples of iron cores were manufactured to study the magnetic properties. After the manufacturing the iron cores were subjected to thermal treatment processes for various temperatures and various periods of times.

After heat treatment of the cores, they are insulated and then a copper wire coil of 200 turn is wind upon the cores. After that magnetic properties are measured to find the relation between the excitation current applied to the coil and the voltage measured on coil terminals.

In this thesis we used OMICRON CT ANALYZER standard package to find the V-I characteristics of the cores

**Key words**: Current Transformer, Magnetization curves, Heat treatment.

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# ÖZET

## AKIM TRAFORMATÖRLERİNİN ELEKTRİKSEL DEMİR ÖZELLİKLERİNİN ÇALIŞMASI VE GELİŞTİRİLMESİ

Ammar Al-JANABI

Fizik Bölümü

Yüksek Lisans Tezi

Tez Danışmanı: Doç. Dr. Taylan YETKİN

Bu tezde, akım transformatörü (AT) üretiminde onların davranışlarını incelemek için bir kaç farklı termal ve mekanik işlemler uyguladık ve uygulanan işlemlere göre transformatörün özelliklerinin değiştiğini gördük. Üretilen akım transformatörleri, AT'nin optimum süreci ve optimum işlemini tanımlamak için detaylı ölçümlere tabi tutuldu.

Bu tez, akım transformatörlerinin çekirdeğinde bulunan çeşitli elektriksel demir örneklerinin mıknatıslanma eğrilerinin çalışmalarını da içerir ve en ideal ısıl işlem sürecini elde etmek için gerekli kalite faktörleri işleyiş zamanı, sıcaklık veya soğutma süresinin hızıdır.

Demir korların bazı örnekleri manyetik özellikleri incelemek için üretildi. Üretilen demir korları, çeşitli sıcaklık ve farklı zaman periyotlarında ısıl işlemlere tabi tutuldu.

Korların ısıl işlemlerinden sonra, izole edildiler ve korların üzeri 200 sıra bir bakır bobin ile sarıldı. Sonra, bobin sarılarak uyarılan akım ve voltaj arasındaki ilişkinin manyetik özellikleri ölçüldü.

Bu çalışmada korların V-I özelliklerini bulmak için OMİCRON AT ANALİZÖR standart paket kullandık.

**Anahtar Kelimeler:** Akım transformatörü**,** mıknatıslanma eğrilerinin**,** ısıl işlemlerinden.

# CHAPTER 1

# INTRODUCTION

## 1.1 Literature Review

The study and development of electrical steel for transformers iron cores have been conduct in two parallel ways: (i) development of grain oriented steel and (ii) reduction of iron losses. During these development methods for measuring the core loss and magnetic properties of magnetic materials have much improved, helping to produce better electrical iron for current transformers (CTs).

### 1.1.1 Development of Oriented Grades

Grain oriented steel has been developed from 1930s to give better grades for industry needs. We give a short historical timeline below with key findings reported in each publication.

At 1933: The first patents on grain-oriented electrical steels issued. Prior to that date, intensive laboratory studies of these steels, as well as the development of special production equipment, were underway at AK Steel (formerly Armco). Before Grain-Oriented grades AISI Types M-10 and M-9 were first commercial produced several years of studying development work were required. Less than ten years later M-8 had been produce with improved magnetic properties.

At 1947: The first catalog containing design, AK published curves and other essential information on grain oriented electrical steel.

At 1955: New oriented grades, M-7 and M-6, had been developed and became the most widely used grades steel. Later, AK Steel 12-mil Oriented M-5 and 11-mil Oriented M-4 with still better magnetic properties were developed.

At 1969: AK Steel introduced Oriented M-3 produced in 9-mil thickness, later to produce in 11-mil thickness.

At 1972: AK produced new materials called them TRAN-COR H Electrical Steels, which have higher degree of grain orientation.

At 1984: Two new materials, AK Steel 9-mil TRAN-COR H-0 and 7-mil Oriented M-2 were developed that provided lower core losses with thinner materials than ever before possible in conventional electrical steels [1].

### 1.1.2 Reduction of Iron (Core) Losses

At 1940 to 1960: The development of grain-oriented electrical steel sheets with controlled crystal orientation contributed greatly in the reduction of iron losses and secured silicon contents as high as 3.25% with no significant decrease in saturation magnetization. Subsequently, reduction of iron losses continued thanks to development of technology for reduced impurity in the steel, which decreases steel sheet thickness and insulating film. In the 1970 higher integration of crystal orientation was develop, which had given rise to further decrease in iron losses. In 1980 thanks to the development of technology to refining the magnetic domain, hysteresis losses has been reduced [2].

At 1974: AK described and discussed the influence of various processing parameters, such as addition of elements, heat treatments, and alloy composition on the mechanical and the magnetic properties and the developments in methods of measuring iron losses regarding Si-Fe alloys. As for Ni-Fe alloys, the effects of refining reagents or added elements adjusting the formation of the super lattice Ni3Fe on the magnetic properties were also given. Moreover, systematic studies on the relation between degree of order and magnetic properties of Ni-Mn alloys were reviewed [3].

The parameters affecting on the improvement of magnetic specifications for electric iron used in the electrical transformers, specifically that used in the iron core of a transformer, can be divided into two groups according to their impact on the iron core losses, and also there effect on the eddy current, and the magnetic hysteresis session. The first group is the parameters affecting the eddy currents: With these parameters to minimize losses by adding silicon to iron content (up to = 3 wt %) leads to increased electrical resistance and thus reduce losses resulting from the eddy currents in the plate.

In the case of increasing the proportion of silicon over the limit (up to 3 wt%), this leads to brittle steel, which in turn leads to lack of potential rise in temperature in the cold rolling process, in order to get the sheet with desirable thickness (0.18mm-0.3mm). Other important parameters are to reduce the thickness as it leads to reduce eddy currents by reducing the size-involved form the variable magnetic flux. Another parameter which materially affects the core iron losses (which is known as the phenomenon of unusual losses) is significantly associated with spacing in which the strip under the application of the external field. It used to reduce eddy currents losses also by increasing the number of domain walls and to increase the average speed.

The second group is parameters affecting the magnetic hysteresis: Parameters affecting the texture in various stages of industrialization to obtain the desired grain with GOSS orientation is [001] [110] with the easier direction of magnetization [001] and it is very close to that direction of rolling (tilt and spread angle $<2°$). In this way, under the following conditions: H=800 A/m, B=1.94T one can get positive effects to reduce the magnetic hysteresis loss, which reflects the total losses in the iron core. To reach the goal of optimal control variables that control GOSS toward to the grain selective, it is necessary to take into account the following distributed grain size on a different textural component the nature and distribution of the particles of the second phase the starting of texture. In addition, grain growth can controlled from the included temperatures annealing [4].

### 1.1.3 Methods for Measuring the Core Loss and Magnetic Properties of Magnetic Materials

A review of methods and techniques which have been investigated and used by numerous researchers in order to measure the power loss in electrical steel sheets from the obtained magnetic properties $B_x$, $B_y$, $H_x$, and $H_y$.

At 1961: Kaplan used cross samples under various flux conditions ranging from a pure alternating flux with a pure rotating flux for measuring the core losses of grain-oriented and non- oriented silicon iron. He found that the grain-oriented iron was a lower loss material under all flux conditions, but this is not always true. Since a grain-oriented steel sheet has stronger anisotropy due to a texture, which causes higher hysteresis loss, the rotational core loss in grain-oriented steel sheets can be higher than that in non-oriented steel sheets [5].

At 1965: Boon and Thompson used an improved thermometric method for measuring the alternating and rotational core losses at 50 Hz under various flux densities for both a hot rolled and cold rolled 3% silicon iron in a square sample of 0.33 mm laminations. They found out that the ratio of rotational loss to alternating loss at 50 Hz in four squares Si-Fe samples was about 2:1 over a wide range of flux densities except at high flux densities [6].

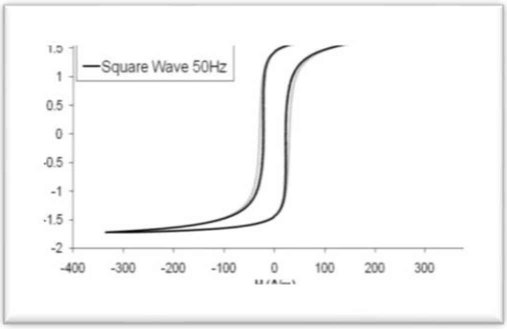
At 1990: K. Ueno et al. They explained domain structure in 3% SiFe found single crystal with glass film changed when annealed at 800°C. The stress relief annealing at 800 °C excludes subdomain, and this makes the domain walls to diverge widely at an angle of 180° as in the case of without stress. This explains why the sharp decrease in the iron core losses in alternating flux magnetization. Because of local stress happens, the domain refining is attributed to the magneto elastic interaction between the transverse magnetization and the tension introduced with subdomain into the steel [7].

At 1997: According to Saitz there are two ways that can be used to analyze and evaluate the core loss in electrical steel sheets. The first way that has to be use is associated with a basic sample of the core that arrangements with insularity and cancellation the iron loss effects from the field calculation. After explaining the magnetic field by means of the basic sample, the calculation of the iron loss can assessed by using the empirical or semi empirical formula, which respects the alternating and rotating flux situations in expressions of magnetic field strength and magnetic flux density.

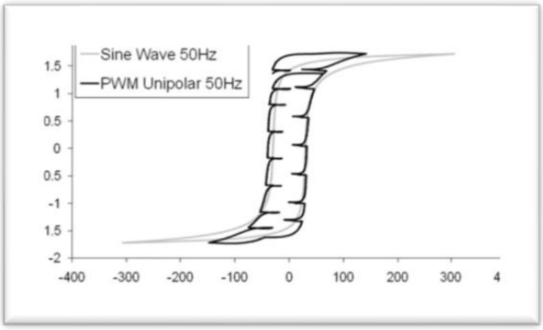
The computational approach that includes all strategies addressing the magnetic field calculation considering the iron loss is the second way, which will followed to calculate the iron loss precisely. These strategies will combine with the magnetic field analysis; therefore, the inclusion of the iron loss effects through the procedural method of the magnetic field taken under consideration [8].

At 2010: C. Patsios, et al. introduced a particular finite element model for iron loss evaluation depending on dynamic and excess losses. This model has capable to represent both the waveform and time variations of the field inside the laminations. They found that the development model in all cases has a high accuracy in iron losses predication. In the square cases, they obtained hysteresis loops, bipolar and Unipolar PWM supplies are compared with the typical sinusoidal excitation as illustrate in

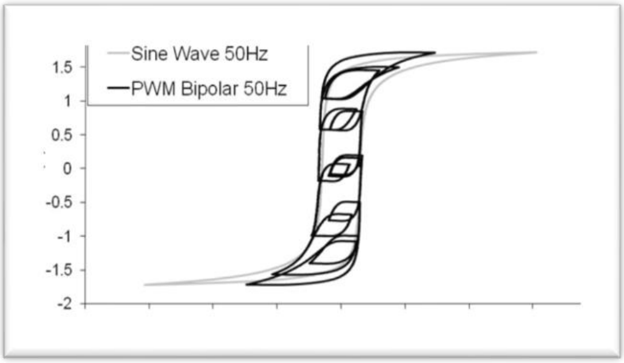
Figures 1.1 a, b and c. The importance of minor loop can observed in the case of bipolar PWM supply [9].




(a)




(b)




(c)

Figure 1.1 Comparison of BH loop measured under sinusoidal excitation to those obtained for different excitations at 50 Hz fundamental frequency [14].a) Square wave b) Unipolar PWM at a switching frequency of 500 Hz and c) Bipolar PWM at a switching frequency of 500 Hz

## 1.2 Objective of the Thesis

This thesis includes studying the magnetization curves or induction curves for various samples of electrical iron that are used as cores in current transformers and the factors that most affect their quality to obtain the ideal heating treatment process such as varying the treatment time, temperature or the rate of cooling process. To remove the stress of the iron core and get a suitable magnetic properties of the iron core, in order to operate a CT appropriate standard conditions.

## 1.3 Hypothesis

Heat treatment process is the most important factor that affects the quality of electrical iron cores in current transformers. Even with the use of a normal industrial furnace as heating element a most suitable heat treatment cycle can be obtain that produces the maximum magnetic properties in transformers cores.

# CHAPTER 2

# GENERAL INFORMATION

## 2.1 Electrical Steel

Electrical steel also known as silicon steel and steel transformers.This steel dedicated to the production of iron cores of electromagnetic equipment. The main property, which makes steel very important, is due to having high magnetic properties, such as a small loop hysteresis (low energy loss per cycle) or low iron core loss, as characterized by high magnetic permeability.

Electrical steel usually made in a cold rolling manner in the form of sheets and then overstocked to formation the iron core.

Electrical steel is an iron alloy that can contain silicon from zero to 6.5% (Si: 5Fe).Commercial alloys usually contains 3.2% of silicon. Controlling this percentage is very important. Although its increased value may increase the fragility of steel during processing of cold rolling, the silicon in iron leads to increased electrical resistance of the material and, as a result, reduction in eddy currents and the magnetic hysteresis loop area. Increase in the content of silicon more than 3.5% also lead to reducing the saturation intensity. This requires the highest exciting currents at high flow density. There are several types of electrical steel:

- **Non – Oriented electrical steel**: The electrical steel, which has magnetic properties that are practically the same in any direction of magnetization in the plan of the material (NOES).
- **Grain Oriented electrical steel**: The electrical iron, which owns the magnetic properties that, is strongly oriented with respect to the direction of rolling process. The electrical steel known, as GOES or GOSS, and they are iron-silicon alloys. This alloy has useful properties such as high permeability and low core losses, which are required for efficient electrical transformers. In this type

of crystal steel, it can be magnetized the material more easily in a direction parallel with the edges of the cube. Usually oriented silicon steel alloy content 3-3.5 % silicon and the effects of the proportion of silicon in the alloy is described previously.

- **Fully processed**: The electrical iron for these types have magnetic properties is that developed by the steel producer. The fact that this name derived from the material completely processed, used without any additional processes to obtain the required magnetic properties.
- **Semi – processed**: The electrical iron for this type are finished to final thickness and physical form (coils, sheets) by the producer, but it has not been fully annealed for magnetic quality final [1].

## 2.2 Iron Losses

The energy losses in transformers divided into two categories

- Copper losses in the coils called load losses
- Iron core loss called non-load losses

The most important factors, which affect the efficiency of transformers, are the copper and iron core losses. When they are take into account in the production (as well as to reduce their costs), the efficiency of the work of transformers can maximized and power output cost can minimized.

The iron core losses, in general, can be dividing into two categories:

- Hysteresis losses in the iron core laminations
- Eddy current losses

### 2.2.1 Hysteresis Losses

When a magnetic field or magnetic force applied on the magnetic material, it leads to the magnetization of the sample until material reaches to the saturation point as shown in the Figure (2.1) as $B – H$ curve. When the magnetic field removed from the sample note, that curve returns to zero. This return, however, will not be identical with the first saturation curve, and this called hysteresis effect. We also note from Figure (2.1) that the value of $B$ when $H$ is equal to zero is called remaining flux density in the sample. During reversal of the applied magnetic field, the state of the demagnetization appear on the sample as in Figure (2.1) and curve OC it is called coercive force. When the applied magnetic force increased on the sample in the same direction the curve, reach to the saturation point D in the opposite direction. By reducing the applied magnetic force we notice that curve is back to the zero point, and increase the force applied to a higher value curve take the same first path to reach to the saturation point A. Finally, note the shape DEFA loop is complete, and it called the hysteresis loop.

To calculate power losses by hysteresis losses in the iron core, consider *A* is a section area of the iron core, *l* is circumference, *N* is number of turns of the coils and let *i* is the instantaneous value of the magnetization current. Then the magnetizing field strength given by equation:

$$H = \frac{Ni}{l}\frac{amper.turn}{metre} \tag{2.1}$$

If the value of the induction at the instant is *B*, then *e* is the induced voltage in the coil:

$$e = \frac{Nd\emptyset}{dt} \quad = \frac{NAdB}{dt} \tag{2.2}$$

Induced voltages will oppose to the current flowing at that instant, thus energy dissipative to maintain the increases current, as in the following equation:

$$= ei = \frac{lAHdB}{dt} \quad (watts) \tag{2.3}$$

This is the power at any instant. Work done in time *dt*

$$= \frac{lAHdBdt}{dt} = lAHdB \;\; (joules) \tag{2.4}$$

Therefore, total work done for one cycle

$$= lA \int HdB \quad (joules) \tag{2.5}$$

From Figure (2.1) we can see $\int HdB$ for the closed loop is the area of the same loop, as the volume of loop is $lA$. Therefore

$$\frac{work\ done}{m^3} = area\ of\ loop \quad \frac{joules}{m^3} \tag{2.6}$$

The loop area of iron used in the construction of the iron core of the transformer given by equation

$$Area\ of\ loop = KB_m^n \tag{2.7}$$

Where *k* is constant, $B_m$ is flux density and n is an empirically determined constant is in the range of 1.6-2.0 [10].

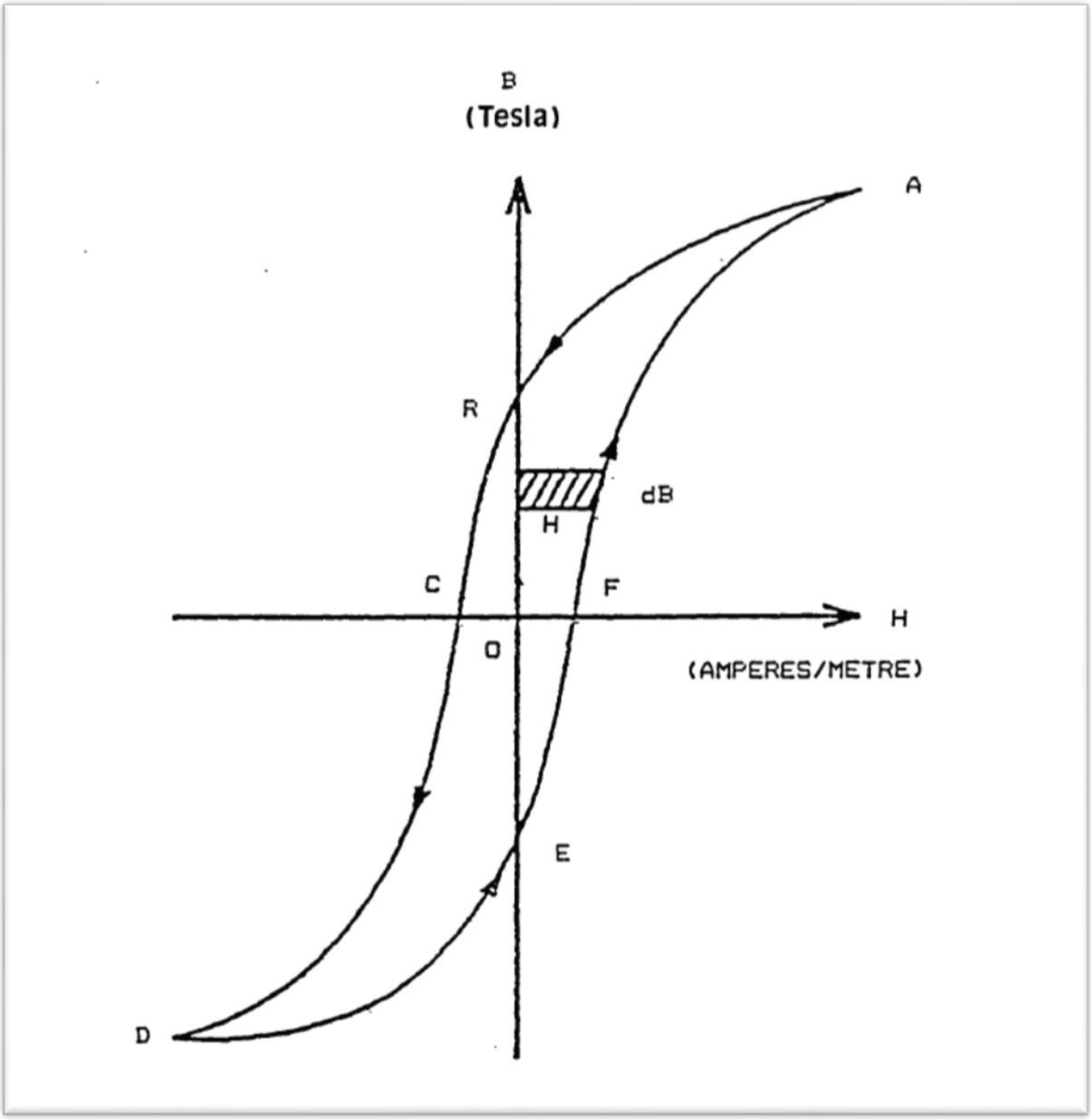



Figure 2.1 Hysteresis loop of a typical ferromagnetic substance [10].

If the material exposed to magnetization during (*f*) cycles per second, then the power dissipation during the second cycle in the hysteresis loop proportional to the frequency (*f*), and thus the dissipative power in the iron core from hysteresis losses is given by:

$$P_h = K_h f B_m^n \qquad (2.8)$$

Where ($k_h$) is, constant depends on the type of magnetic material used in the construction of the iron core and the dimensions of the Iron core [10].

### 2.2.2 Eddy Current Losses

Variation in the magnetic field applied to the magnetic material with time generates induce voltage around a closed path that taken by magnetic flux lines. The current generated in conductor because of induced voltage and these currents called eddy. Eddy currents cause undesirable thermal losses. To reduce these losses in transformers, the iron cores are manufacturing from thin laminations and isolated by coating by thin film. They assembled in a manner parallel to the direction of the magnetic flux path.

As shown Figure (2.2), it is possible to calculate the eddy current losses by a classical method. Where $d$ is lamination thickness. Length and depth take as one. The field $B$, which is varying sinusoidally in the direction that appears in the Figure (2.2):

$$B = B_m \sin \omega t \tag{2.9}$$

Where the fields flux $\emptyset$ is

$$\emptyset = 2xB_m \sin \omega t \tag{2.10}$$

The induced voltage that generating from pulsating flux given in the following equation

$$e = \frac{d\emptyset}{dt} \tag{2.11}$$

$$e = \frac{d}{dt}(2xB_m \sin \omega t) \tag{2.12}$$

RMS voltage given as

$$E = \frac{2\pi f}{\sqrt{2}}(2xB_m) \quad volt \tag{2.13}$$

The current flowing in the sheet element $dx$ with up and down direction represented in the following equation

$$I = \frac{E}{\frac{2\rho}{dx}} = \frac{Edx}{2\rho} \tag{2.14}$$

The Electrical Resistivity of sheet is ($\rho$). Therefore, the dissipative power in $dx$ is $P_{dx}$:

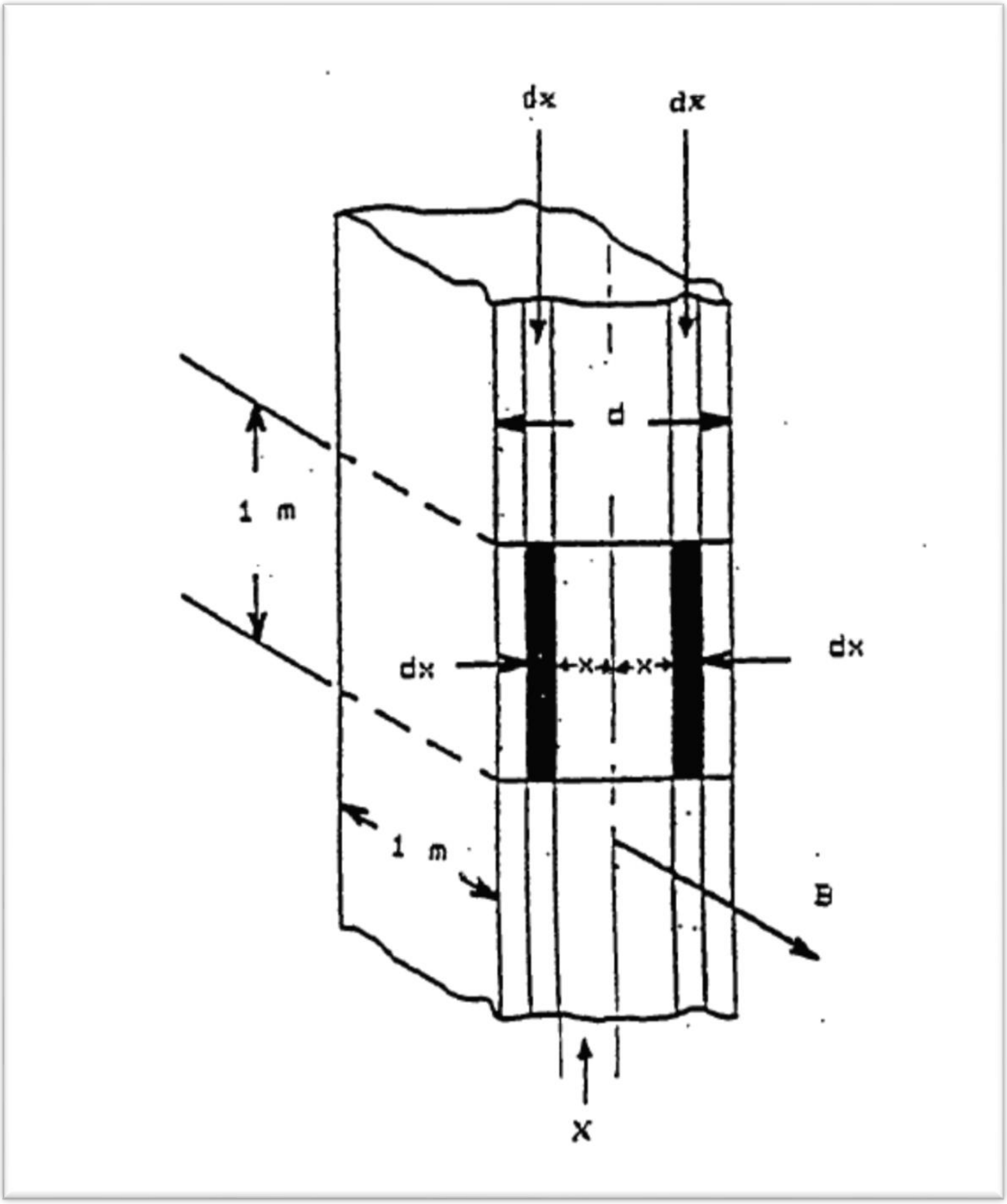



Figure 2.2 Calculation of eddy current loss [10].

$$P_{dx} = EI = \frac{(4\pi^2 f^2 x^2 B_m^2 dx)}{\rho} \tag{2.15}$$

According to equation (2.15), dissipative power in the sheet is

$$P = \int_0^{\frac{d}{2}} P_{dx}\, dx = \frac{4\pi^2 f^2 B_m^2}{\rho} \int_0^{\frac{d}{2}} x^2\, dx \tag{2.16}$$

Then we find

$$P = \frac{\pi^2 f^2 B_m^2 d^3}{6\rho} \quad \text{(Watt)} \tag{2.17}$$

From the volume of element sheet (*d*) in cubic meter, the eddy current losses per volume unit ($P_{ec}$)

$$P_{ec} = \frac{(\pi f B_m d)^2}{6\rho} \quad \left(\frac{watt}{m^3}\right) \tag{2.18}$$

From equation (2.18), it can conclude that the eddy currents losses are proportional with $d^2$ and inversely proportional with ρ. Therefore, use of high-resistance materials such as silicon in steel, has a resistance estimated by several times compared with the normal steel sheets [10].

### 2.2.3 Total Core Losses

It can conclude from the above that the iron core losses can represented as the collection of hysteresis losses and eddy current losses [10].

$$P_{hy} = K_h B_m^n f \qquad \left(\frac{w}{m^3}\right) \tag{2.19}$$

$$P_{edd} = K_e B_m^2 f^2 d^2 \qquad \left(\frac{w}{m^3}\right) \tag{2.20}$$

Therefore, the total loss is:

$$P = P_{hy} + P_{edd} \tag{2.21}$$

$$P = K_h B_m^n + \frac{K_e B_m^2 f^2 d^2}{1} \tag{2.22}$$

The total losses for each cycle given as:

$$\frac{\rho}{f} = K_{h'} + K_{e'} f \tag{2.23}$$

$$K_h' = K_h B_m^n \qquad \text{(Hysteresis loss/cycle)} \tag{2.24}$$

$$K_e' = K_e B_m^n f^2 d^2 \qquad \text{(Eddy current loss/cycle)} \qquad (2.25)$$

## 2.3 The Factors Influencing Iron Losses

A few factors will influence in iron losses. Among these, the diverse production ventures of electrical machine stator loops center affect the iron losses extensively. Figure (2.3) gives a synopsis on run of the mill affecting elements all through the productive technique for electrical machine centers. The aggregate disintegration impacts on the material attributable to the cutting related total delivering venture along researched for an electrical magnet machine with a non-situated electrical steel stator curl center in [11]. A posteriori estimations of the delivering strategy impacts in actuation machines are give in figure below [12].

The resulting subsections describe the three productive steps in more details.

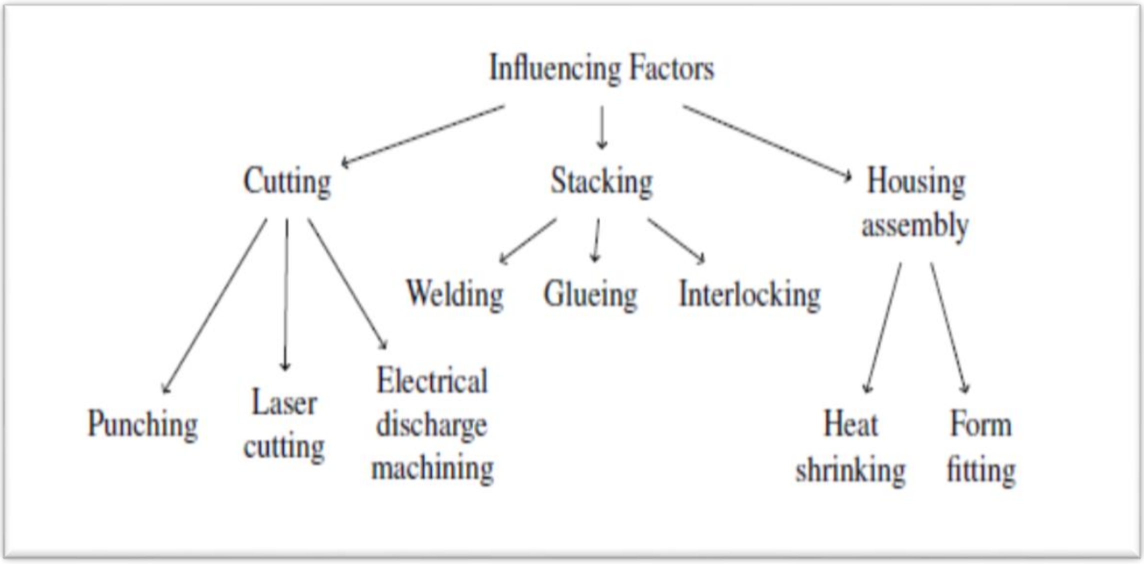



Figure 2.3Influencing factors of the manufacturing process of electrical machine cores [11]

## 2.4 Stress

Stress is a measure of forces intensity that the object exposed. Electrical iron exposed to variety of mechanical stresses affects the magnetic characteristics, and this leads to reduction of efficiency. Typically, there are processes to relieve stress and in effect, the result is a class of iron material with better magnetic properties.

## 2.5 Magnetic Properties of the Iron and the Effect of Stress

The ferromagnetic materials gain good magnetic properties through the presence of domains, which formed in the material structure. Each domain has a particular direction in magnetization. These domains distributed randomly in a piece of metal and the net effect of this magnetic field is a zero in the absence of an external magnetic field. When there is an external magnetic field, these domains start to grow and magnetic moment aligns with the applied field in the same direction. This leads to make the permittivity and high magnetic flux appear on it.

During manufacturing, one can improve magnetic properties of the iron through the formation of mineral crystals and make them line up in a certain direction, This process gives high magnetic properties as in orientated electrical steel (GOES), which the magnetization is in direction with the direction of the magnetic sheet, and this type is typically used in electrical transformers. There is another type of iron, which does not have the formation of crystals in a specific direction when manufacturing, it called Non Oriented Electrical Steel. This type of iron used in the electric motor industry.

Both types described above and other types of electric iron, when they exposed to mechanical stresses have their domains affected. Domains change their formation because of the applied stress, which requires removing that stress, in order to return the crystal structure to the optimum position.

Developments in the oriented silicon steel industry (GOSS) led to the discovery of grain oriented steel (Cold Rolled Grain Oriented Silicon Steel) or the so-called Conventional Grain Oriented Steel CGO and is the most common type that is used in the transformers today. In this type electric steel crystalline lattice has representation [110] [001] by Miller crystalline guide systems crystals in metal (Miller Index). The guide means that the steel is composed of crystalline granules which level [110] perpendicular to the direction of rolling in these grained level [001] parallel to the direction of rolling and parallel to the ribs cubic crystal as in Figure (2.4).

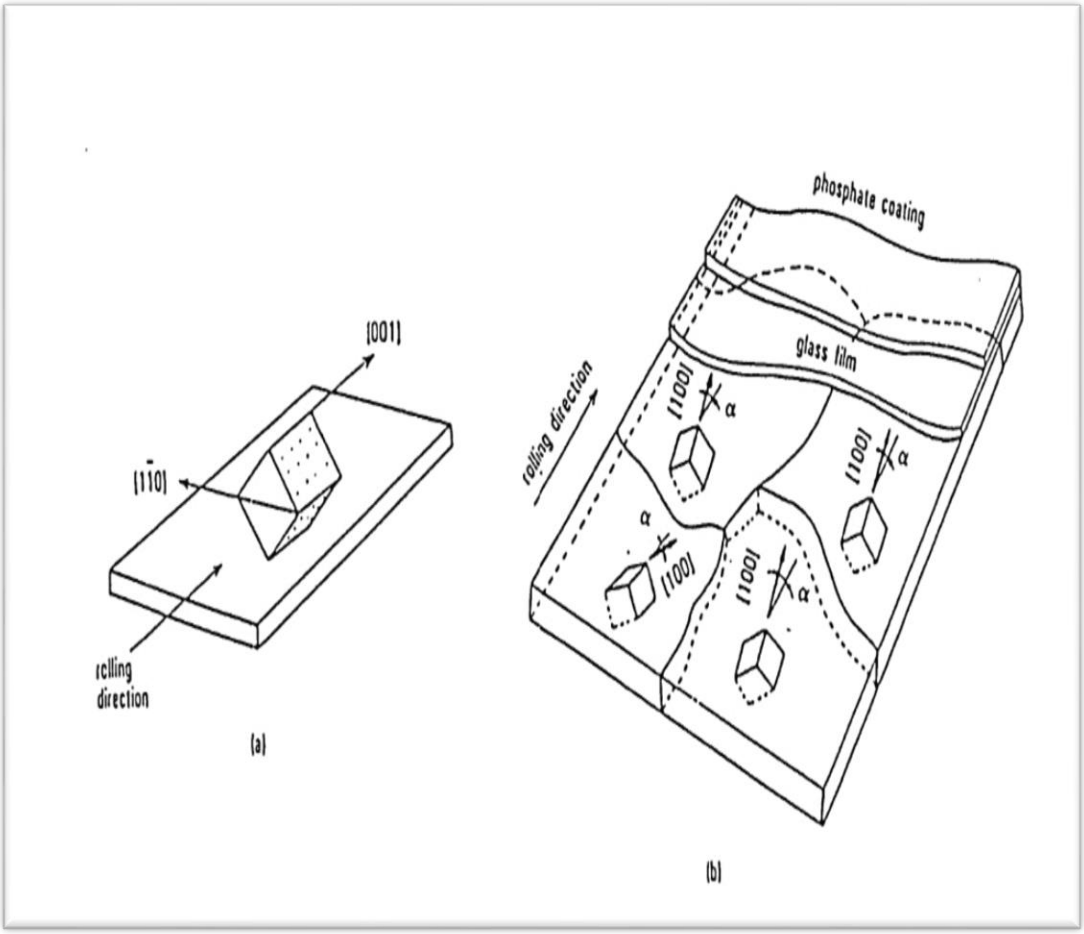



Figure 2.4 Formations the crystals in the oriented silicon steel [10]

The effect of mechanical stress on the electrical steel appears during the manufacturing of the product. For example, if the product is the heart of the transformers distribution of the kind wound core or the core of the toroidal core for current transformers, generated strain is the result of folded iron strips and this forces it to take shape ring. When manufacturing in stator or moving the electrical motor the iron steel can get perforation. In these cases, stresses generated because of perforation, and stacks, slitting sheets, and applied cuts affect the magnetic properties of the core more, which lead to make it worse. Therefore, this stress should be relieved. While the production of distribution transformers with cores gathered strips (stacking transformers) is not the issue, this requires removing stress because of their formation during the production of these type operations.

It is possible to recognize other reasons that affect the iron magnetic properties badly due to mechanical strain, which are resulting from several manufacturing factors, such as:

- Shearing: it is necessary for cutting iron by using cutters to obtain certain dimensions.
- Slitting: it is necessary to obtain the appropriate width of the strips.
- Punching: as it get to the fixed part and rotor part of the motor.
- Bending: it is also in the cores of current transformers.
- Press: to change the form for example of a circular to square as it gets at the core of the cabbage transformers.
- Accuracy sheets fabrication as few ripples in the strips resulting from manufacturing up to a regular 3mm / m exist, there are also distortion surface of the sheet lead to straining at the structure of the iron sheet when it is formation [10].
- Stamping: it gets as a result of assembling slide over each other, as happens when put the screws to form the core of the transformer.
- Thermal changes between the iron core layers

## 2.6 The Purpose of the Annealing Process of theTransformer's Core

The purpose of the annealing process on the electrical steel is to improve magnetic properties in terms of permeability. This process also contributes to reduction of the iron losses that have been addressee previously. The most important advantage of the stress relieve process is a raise the level of saturation of magnetic flux in the iron and a reduction the noise due to magnetostriction in the electrical iron.

From the above we conclude that annealing enhances the production of identical specifications and non-differentiated, which enhances to have confidence product, where one can produce transformers with low losses while maintaining power production of the transformer and the lowest level for amount of iron and low cost.

## 2.7 Requirements to Relieve Stress Process

To benefit from the stress relieve the following processes during annealing must taken into account:

- Reduce the mechanical stress in the iron to the lowest possible level in order to get the best magnetic properties
- Prevent iron interaction of oxygen with or without carbon (for example, which is iron-bearing samples) [13].Maintaining the insulation coatings of iron as high temperatures can remove it. Electric iron is isolated by inorganic materials (C5, Inorganic according to ASTM A976) is consider as appropriate for annealing

processes by using heat temperature up to 850˚C when heated in an inert gas atmosphere, either in the air atmosphere of normal annealing should not exceed 230˚C in order to ensure that no damage paint [14], [15].

Relieve stress process depends on the method of manufacturing of the material and type of annealing equipment used, and shape and amount of the sample. According to *downs* of the rates of temperature, it is important to take into account that the *ups* excitement left in the material after the removal of stress because of the heat. Knowing that the core's temperature is important, not the oven temperature, and this is what makes the calculation of the heating time of the shipment starts from the moment of arrival of the heat the samples to the required degree, where this time varies depending on the amount and the amount of charge placed oven.

Annealing atmospheres can be with the presence of noble gases free of antioxidants factors, such as nitrogen or helium. The use of furnaces (vacuum) for treatment is acceptable, but it must taken into account the lack of heat transfer, which affects the heating and cooling rates, is not recommended that the heat is less than (760˚C) because they lead to a decrease in the efficiency of heat transfer [16].

The annealing process for GOSS according to the product manufacturer, for example given in reference [13], recommends that the annealing temperature ranging between (760-845˚C) and preferably be between (788-816˚C) as well as the atmosphere to be with dry nitrogen to prevent iron oxidation. However, it might recommend adding hydrogen at rates up to 20% in order to verify the non-oxidation. For rates of heating times or cooling of the samples, these rates are critical in some cases due to be thermal stresses on the iron cores, and for the cores of big-sections are more sensitive to these internal stresses that resulting from the rapid rates of heating or cooling. The cooling speed, however, when the temperature arrival to the point less than (370˚C) is impressive and even the preservatives in the atmosphere are not needed under such a degree.

There are two types of furnaces are suitable for removing stress:

- Batch furnaces, which using for various models of iron core, largely and when its production is intermittently or when they are small amounts cores.
- Continuous furnaces, using when need high production rates and volumes cores. For this type furnace there is another benefit that the temperature is stable in the

range allocated which leads to the core of all that is going through the thermal scope. The cores will be subject to the same atmosphere and temperature conditions. Stress relieve begins when the sample arrives to the annealing point of primary temperature (760-845˚C). This normally takes an hour and then starts racing the heat cycle on the sample, taking into consideration that the interior of the cores it has late to reach by the heat from the external surface areas or confrontation heat source and this applies even to the oven with internal fans. It is important to be aware that the rapid heating and cooling rates may distort the iron core shape what calls attention to it. Reference [17] explains that it is recommended for GOES that stress relieve temperature is between (780-820˚C) and then install the heat then a certain time depending on the shape of core and the number and type of oven, but after a homogeneous temperature above, then calculates the survival of those heat . For iron (NOES), the temperature stress relieve is (720-750˚C).

Reference [18] proposes a variety of ways of heat treatment of electrical iron as follows:

1. Annealing process using the batch furnaces: It is proposed to assemble the metal inner cover and then placed in a dry atmosphere during two-hour and temperature ranging (760-840˚C) and practically (800˚C ± 20˚C) with prevent rapid thermal changes by heating or cooling.
2. Annealing process in a mesh belt furnace: put piles of iron sheets for one hour with temperature rate (800˚C ± 10˚C) and in the atmosphere of inert gases.
3. The process of annealing in roller hearth furnaces: It is recommended temperatures (800˚C ± 10˚C) but for (30-60 sec) only in the atmosphere of a normal air, sheets will not oxidized because of the short time annealing, which will prevent oxidation.
4. For the toroidal core: it is possible to conduct annealing process of type 1 and 2 of the furnace with the preservation of the harsh stresses resulting from tweaking and maintaining of Heat exposure to rapid changes.


Figure 2.5 ABB Roller Hearth Furnace Systems [19]

Figure 2.6 ABB Roller Hearth Furnace Systems from another angle [19]

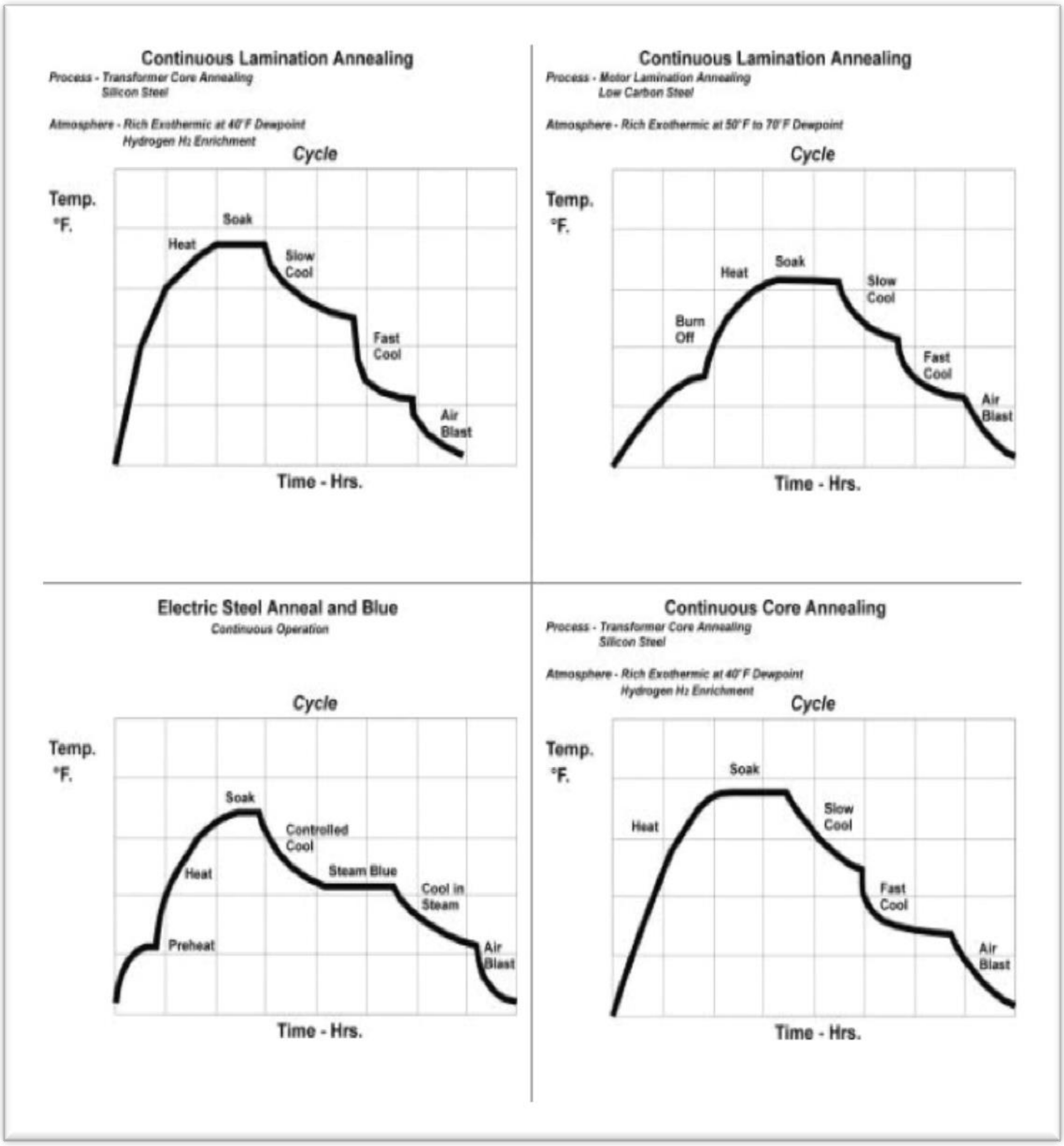



Figure 2.7 Heat treatment cycles for many types of electrical steel [19]

# CHAPTER 3

# CURRENT TRANSFORMER

Transformers used in instrumentation transformer are of several types. The most important type of these is a current transformer, which performs two important functions: the first is to measure the current in an electrical circuit, and the second is to protect the equipment associated with it in the same electrical circuit. The most important functions of current transformers are

- To produce current in the secondary coil by electromagnetic induction method resulting from the flow of current in the primary coil, this is to be measure.
- To provide a ways for measuring high currents by turning them into low currents, this can be measured and commensurate with measurement devices available.
- To provide a control mechanism for which current transformer flowing in the circuit, will protect measuring the value of current for very high electrical currents in electrical circuit. This way, electrical transformers and electrical circuits can protect in the event of rising current values higher than the desired values [20].

The current transformers operate very similar to standard transformers, having primary and secondary coils. The primary coil contains one or a few turn(s), usually being a bus bar or cable passing through the CT hole. Therefore, CT also knows as a “series transformer” because of this kind of arrangement. The primary coil is asynchronous with the current carrying conductor. On the other side, the secondary coil is composed of a large number of turns compared to the primary coil, which may be up to several hundreds of turns. It wrapped around the iron core of transformer. The wire used in secondary coil has a small cross-section area because the flow current passing through it does not exceed 5 A [21].

Current transformers can be dividing into three types:

1. Wound current transformers: primary coil of transformer connected asynchronous with the conductor, which carries the current to be measuring. The current in the secondary coil depends on the ratio of the number of turns in primary and secondary coils.
2. Bar-type current transformers: In this type of transformer, the toroidal does not have primary coils as number of turns. Instead, it uses a bus bar or a cable, which is in the system, and it behaves like one turn primary coil. Because of this, the transformer is isolated from the high voltage circuit.
3. Toroidal current transformers: This kind of CT does not contain a primary coil. The road that carries the current flowing through the circuit is a rib passes through the toroidal transformer window [21].

The current in the secondary winding must be directly proportional to that in the primary winding which is measuring at standard operation conditions. The phase angle of the secondary current will be slightly different (nearly zero) from the primary current of the transformer. Therefore, the CT must achieve high precision current ratio between the primary and secondary windings and reduce the phase angle error to a minimum. The error in the phase angle and the ratio are the result of the loss in ampere-turn of the primary winding to magnetize the iron core, which leads to reducing the required ampere-turn to induce current in the secondary winding.

### 3.1 Phase Diagram for the Current Transformer

The phase diagram helps in understanding the design of the current transformer and determines its accuracy class, through which the CT can analyze and the parameters that most affect the accuracy can be determined and possibly their effects would reduced. For example, through the phase diagram the effect of the induced current $I_e$ on the accuracy class can be derived which plays a major role in designing a CT with an appropriate accuracy regarding the errors in the phase and current ratio.

With the help of the CT equivalent circuit Figure (3.1) and considering the following points we see that

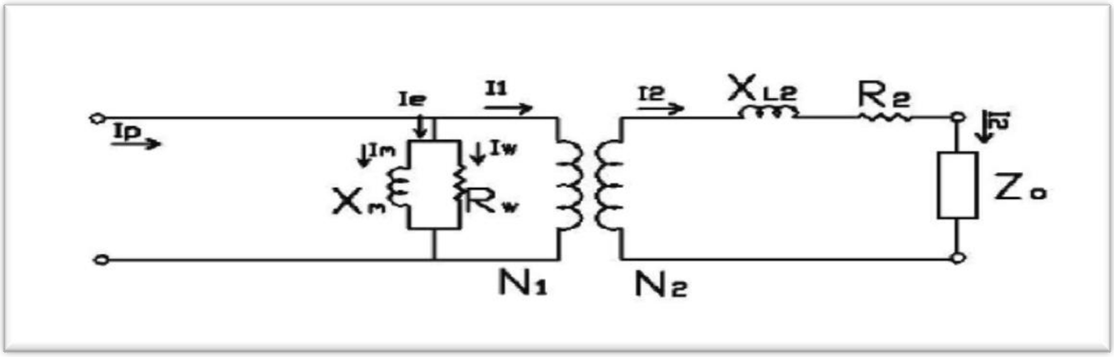


Figure 3.1 Current transformer equivalent circuits with no primary winding impedance [20]

a) The magnetic flux ($\varphi$) considered as the main horizontal axis, which is the common axis for the primary winding circuit.

b) $E_p$ is the electromotive force of the primary winding which lead the magnetic flux by ($90^o$).

c) Es is the induced electromotive force for the secondary winding, which is at 180° phase difference with $E_p$.

d) $I_p$ the primary current which has two components; one is very small called induce current ($I_e$) and a large one, nearly equal the total primary current, this component is in the opposite direction to that of the secondary circuit.

e) $\delta$ is the phase angle between the secondary current and secondary winding electromotive force.

f) $\alpha$ is the phase angle between the flux ($\varphi$) and the induced current ($I_e$).
The phase diagram can be drawn as shown in Figure 2.2

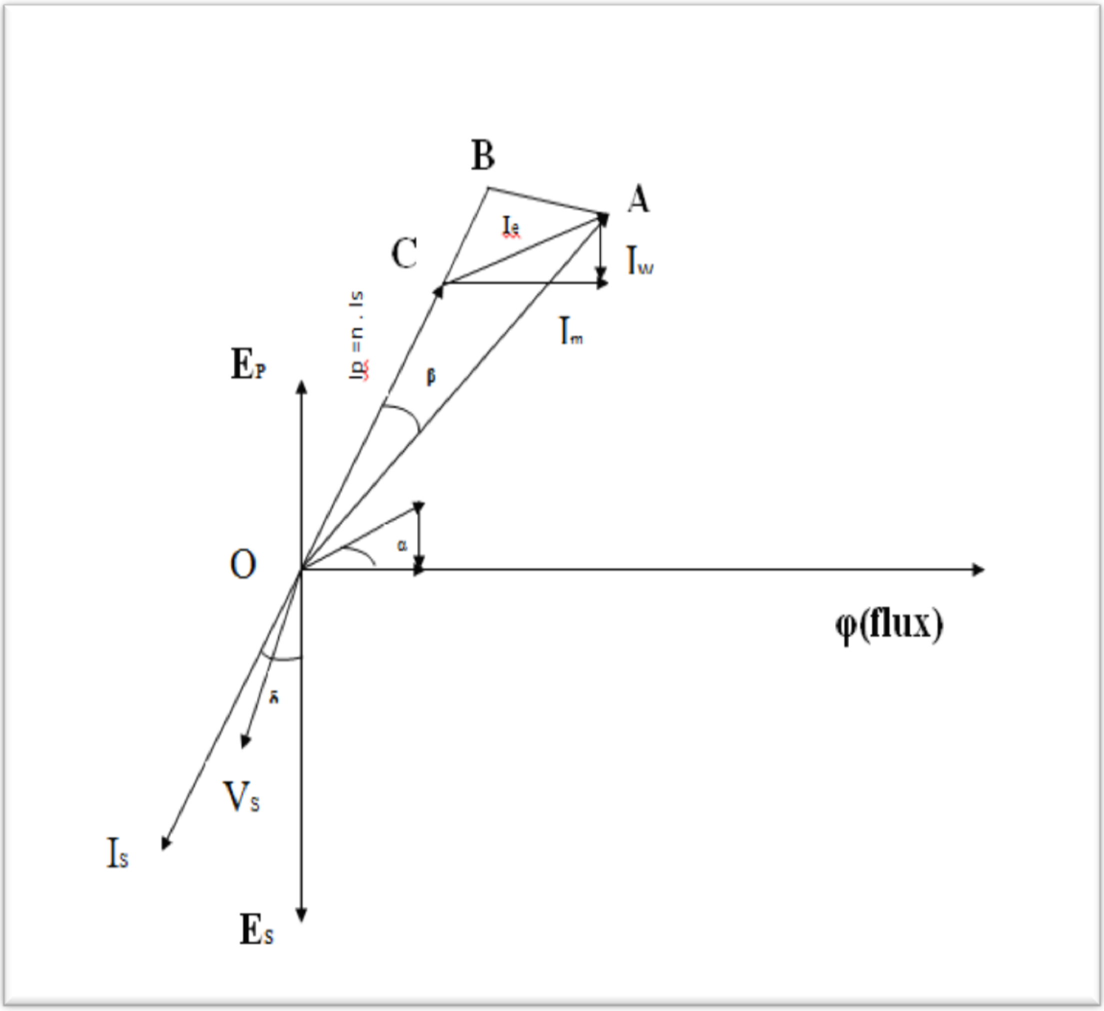



Figure 3.2 Phase diagram for a current transformer [20]

## 3.2 Induction Curve

The main parameter that causes the measurement errors in the current transformer is the induced current ($I_e$) which consist of two components ($I_m$) which induces the magnetic field and magnetize the iron core, and ($I_w$) which is usually lost as heat in the iron core as a result of eddy currents and hysteresis loss in the transformer.

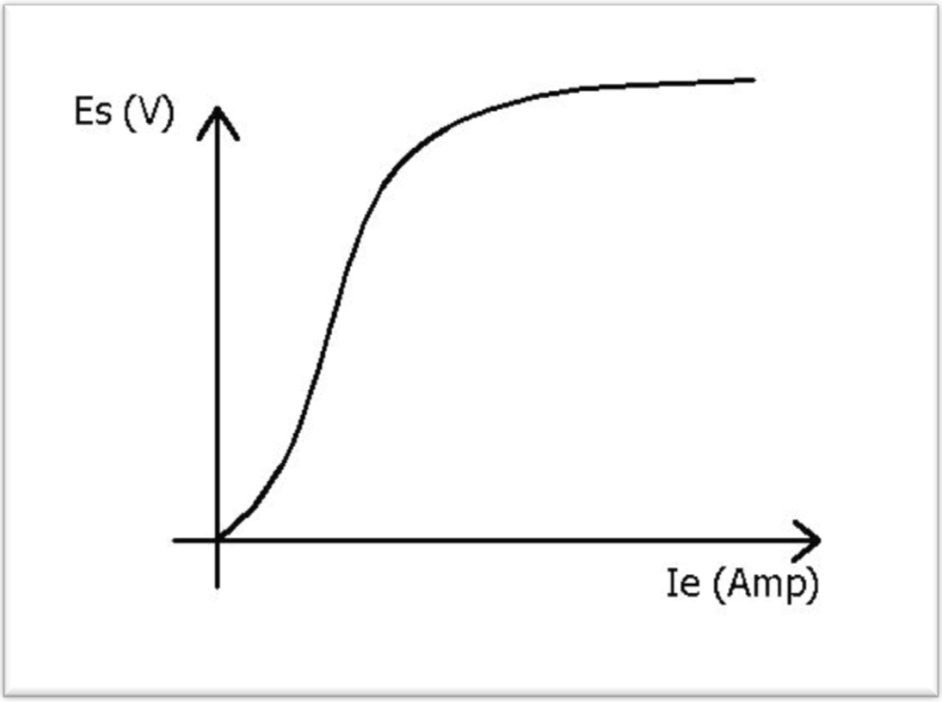



Figure 3.3 Relation between the induced current and current transformer voltage

The accuracy of a current transformer can calculate at any load when its secondary induction curve and the secondary circuit impedance knowing.

### 3.3 The Iron Core and Its Losses

The iron core is an effective part of the current transformer. It constructed by stacking layers of thin highly permeable electrical iron lamination assembled to provide the required magnetic path. These laminations are electrically insulating from each other by a very thin coating of insulating varnish or by other non-conducting insulation. As well as given that a little unwillingness path for the B, the core is modeled to prohibit passing ($I$) in the iron core. These passing currents, called "eddy currents", cause energy and heating loss in the core reducing the transformer efficiency. These losses mostly as a result of ($V$) produced in the core circuit that is continually exposure to the exchanging ($B$) applied by supply voltage. Another source of energy loss in the iron core is hysteresis loss, which caused by the residual magnetization retained by the core material. To reduce this type of energy loss in the current transformer core, Grain Oriented Silicon Steel (GOSS) usually used for its high permeability and low power loss [13].

The mechanism and processes to reduce each of the iron core losses are diverse which makes it so difficult to reduce them simultaneously. One of these processes is the heat treatment, which is a process to relief the mechanical stresses that resulted from manufacturing and bending of the iron core.

Heat treatment process in addition to the types of electric iron cores, their properties, and the reasons for using GOSS in current transformers will be discuses thoroughly in the next chapter.

### 3.4 Why Using Induction Curves

It well known that the magnetic properties of the electrical steel (electrical iron) determine the relationship between the magnetic field intensity ($H$) and the magnetic flux density ($B$). They are related to each other by the relation $B = \mu H$, where $\mu$ is the permeability of iron which is the most important characteristic that distinguishes good electrical iron from others.

The relationship between $B$ and $H$ for iron is usually plotting for standard samples in the form of laminations using devices that can sense the flux density and the magnetic field intensity. The problem arises when applying this method for the iron cores of current transformers, which are toroidally, shaped (not laminations as the case for standard samples), this alters the magnetic properties of iron due to mechanical stress resulting from bending the iron to obtain the toroidal shape.

In this thesis study, all the measurement for $B$-$H$ relation are carried out on the toroidal samples to investigate the effect of bending and find out the best means to deal with it.

Measurements of $B$ and $H$ require sophisticated devices and standard iron samples that differ from the actual core samples that using for current transformers. Therefore, this study has been replacing by measuring the current and voltage to obtain, which knowing "induction curve”. Measuring the induction curve is the usual method adopted by many researchers in the literature to find the magnetic properties for iron samples [22].

The relation between the magnetic field intensity and electric current can show by using the magneto motive force.

Magnetic motive force, MMF, is defined as follows [23].

$$MMF = NI \tag{3.1}$$

MMF can also be shown related to $H$ as

$$H\ell = NI \tag{3.2}$$

Thus we obtain $H$

$$H = \frac{NI}{\ell} \tag{3.3}$$

From this result we see that $H$ is directly proportional to $I$. We can also show equation for $B$. from Faraday low:

$$V(t) = N\frac{d\emptyset}{dt} \tag{3.4}$$

Since magnetic flux can be found from magnetic density and area we can show that

$$V(t) = N\frac{d}{dt}BA \tag{3.5}$$

$$= NAB_{max}\frac{d\sin(wt)}{dt} \tag{3.6}$$

$$= NAB_{max}\cos(wt)w \tag{3.7}$$

$$= NAB_{max}\cos(wt)2\pi f \tag{3.8}$$

From

$$V(t) = V_{max} \times \cos(wt) \tag{3.9}$$

Thus we obtain

$$V_{max} = 2\pi f B_{max} AN \tag{3.10}$$

from

$$V = \frac{V_{max}}{\sqrt{2}} \text{ (for normal } A.C \text{ voltage)} \tag{3.11}$$

Thus, we obtain

$$V = \sqrt{2}\pi f B_{max} AN \tag{3.12}$$

$$V = 4.44 \times f \times B_{max} \times A \times N \tag{3.13}$$

From this result, we see that *B* is directly proportional to *V*.

# CHAPTER 4

# EXPERIMENTAL SETUP AND SAMPLE PREPARATION

## 4.1 Introduction

The magnetic properties of the electrical steels are sensitive to mechanical stress, which affects magnetic properties; such as low magnetic permeability, low saturated flux density, and increased losses. These changes occur because the crystal of metal distorted in the strained metal. This distortion in structure affects the relation between the magnetic induction (*H*) and the induced magnetic flux density (*B*).

In this research, a normal heating element industrial furnace is used. This furnace has an ability of reaching 1000 ˚C for heat treatment applications. This furnace used to make a different heat treatment cycles upon the steel cores of CTs in order to find the most suitable heat cycle that produces the optimum magnetic properties in transformers core.

## 4.2 Cores Manufacturing

In this study, 100 mm waste steel layers used to manufacture the iron cores of the CTs. They silted into 25 mm wide layers as shown in Figure 4.1. After that 21 iron core samples were manufactured from grain oriented silicon steel (GOSS) by using a core winding machine, as shown in Figure 4.2 Iron core product, as shown in Figure 4.3. Manufacturing data for the samples detailed in Table 4.1.

## 4.3 Core Winding Machine

The core winding machine model (KT2000/CORTECH) it is fully automatic and high – speed toroidal core winding machine, which owns several advantages, enable us to achieve the required designs accuracy wound toroidal core of up to 140 per hour. (http://www.cortechmachines.com/kt2000.html)

### 4.4 Slitting Machine

Slitting machine (C8005-4/ZF) can be shear material like carbon steel, stainless steel, copper and various special materials. Width for the material up to 150 mm and lamination thickness is 0.05-05 mm, which can slit with shear speed 20 m/min.

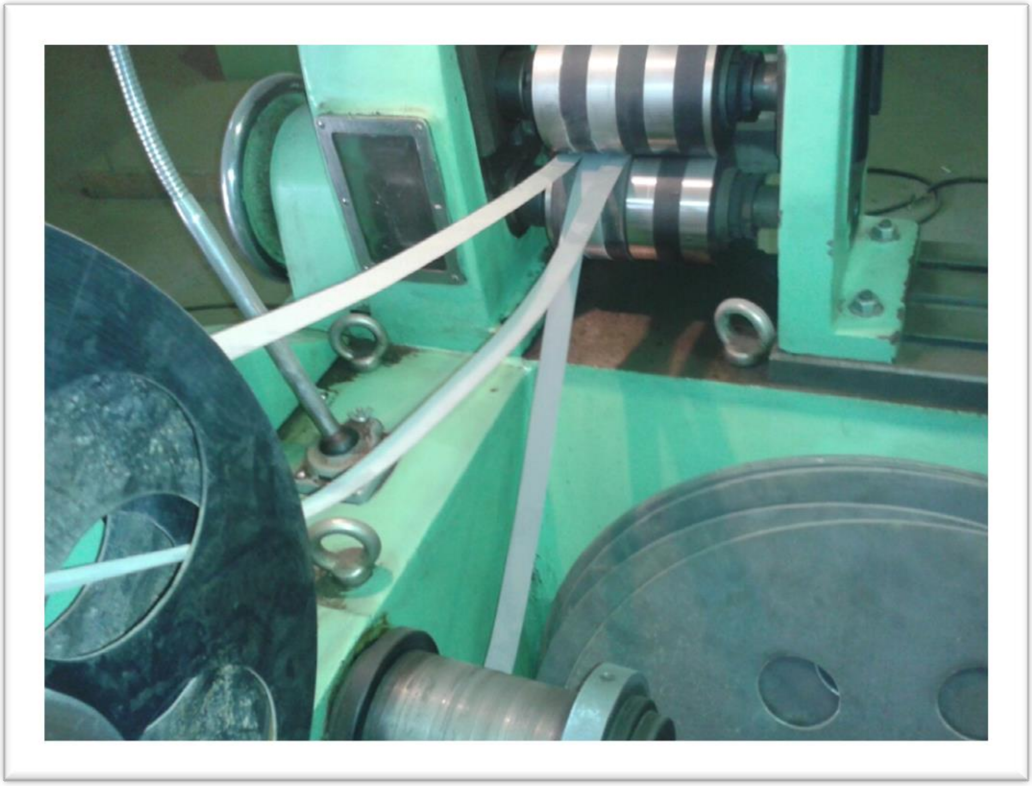


Figure 4.1 Slitting machine (C800-4/ZF-NORTHWEST)

Figure 4.2 Core winding machine (KT2000/CORTECH)

Table 4.1 Manufacturing data of iron core samples

| | |
|---|---|
| Inner Diameter ($D_{in}$) (mm) | 115 |
| Outer Diameter ($D_{out}$) (mm) | 125 |
| Core Width (W) (mm) | 25 |
| Weight (g) | 346 |
| Magnetic Flax (B) (Tesla) | 0.925 |
| Magnetic Field Intensity (H) (A/m) | 22.8 |
| Cross Sectional Area (A) ($mm^2$) | 125 |

Figure 4.3 Iron core products

## 4.5 Heat Treatment

A heat treatment technique conducted after the core winding and slitting operations due to the stress relief considerations. Batch furnace done Heat treatment without using a noble gas. The picture of the batch furnace is show in Figure 4.4. The treatment process done to 18 samples by the means of one cycle for each three samples regarding that every cycle had its own temperature and period. The three remaining samples left without heat treatment to compare them with samples that have been heat-treated process. Cyclic heat treatment detailed in Table 4.2.

Figure 4.4 Batch furnace

## 4.6 CT Preparation and Analysis

A secondary copper coil winded on the electrically insulated iron core to prepare the desired CT with ratio as 1000/5, burden as 15 VA, and 200 turns. As shown in Figure 3.5 manufactured CTs were analyzed using OMICRON CT Analyzer device (see Figure 4.6 which works only with the existence of a complete CT to obtain the data required for the experimental purpose.

Table 4.2 Details of heat treatment

| **Samples** | **Cycles information** | |
|---|---|---|
| | **Time (h)** | **Temperature (℃)** |
| Sample (1, 2, 3) (cycle 1) | 2 | 600 |
| Sample (4, 5, 6) (cycle 2) | 3 | 600 |
| Sample (7, 8, 9) (cycle 3) | 3 | 650 |
| Sample (10, 11, 12) (cycle 4) | 2 | 750 |
| Sample (13, 14, 15) (cycle 5) | 3 | 750 |
| Sample (16, 17, 18) (cycle 6) | 2 | 800 |

Figure 4.5 C.T 1000/5, 200 turn


Figure 4.6 OMICRON CT Analyzer, front view

### 4.7 OMICRON CT Analyzer

In this study, we used OMICRON CT Analyzer Hc 816c to analyze manufactured CTs. The following gives brief information about the device and different pages on the device menu, which is available for detailed analysis. These are

- CT-object
- Resistance
- Excitation
- Ratio
- Assessment

First page: CT-object

In this page the specifications of the transformer are inserted like $I_P$, $I_S$, VA, burden, $R_{ct}$, standard.

Second page: Resistance

This page shows the result of secondary coil resistance test $S_{CC}$ using current, in addition to the adjustment of the resistance values according to the reference temperature (75℃). In addition, values of current and voltage are shown and accordingly after calculating the values of resistance.

Third page: Excitation

This page deals with the specifications of the iron of the transformer to be tested in which [V, I] for the knee point are measured in addition to plot the magnetization curve for iron.

Fourth page: Ratio

In this page all, the conversion results showed as follows [ratio, polarity, phase, N, $I_p$]. In addition to these, there are two tables in the page: (i) transforming ratios depending on burden, $I_p$ and (ii) phase angle between $I_p$, $I_s$.

Fifth page: Assessment

This page evaluates the results for the transformer to test according to the standards inserted in the first page [assessment, rct, pol, and phase].

## 4.8 Sample Preparation

In this thesis, study six groups of CTs have been heat treated at different time durations and temperatures and one group without heat treatment process. Each group had three or six core samples. Temperatures and time durations tabulated in Table 4.3.

Table 4.3 Temperature and time duration for each study group

| Sample Size | Temperature | Time Duration |
|---|---|---|
| 6 | 600 ˚C | 2 hr |
| 3 | 600 ˚C | 3 hr |
| 3 | 650 ˚C | 3 hr |
| 3 | 750 ˚C | 2 hr |
| 3 | 750 ˚C | 3 hr |
| 6 | 800 ˚C | 2 hr |

# CHAPTER 5

## RESULTS AND DISCUSSION

The study groups described in previous chapter analyzes by using CT analyzer. The overall voltage vs. Current graph was show in Figure (5.1). It shows all 18 samples with different colors.

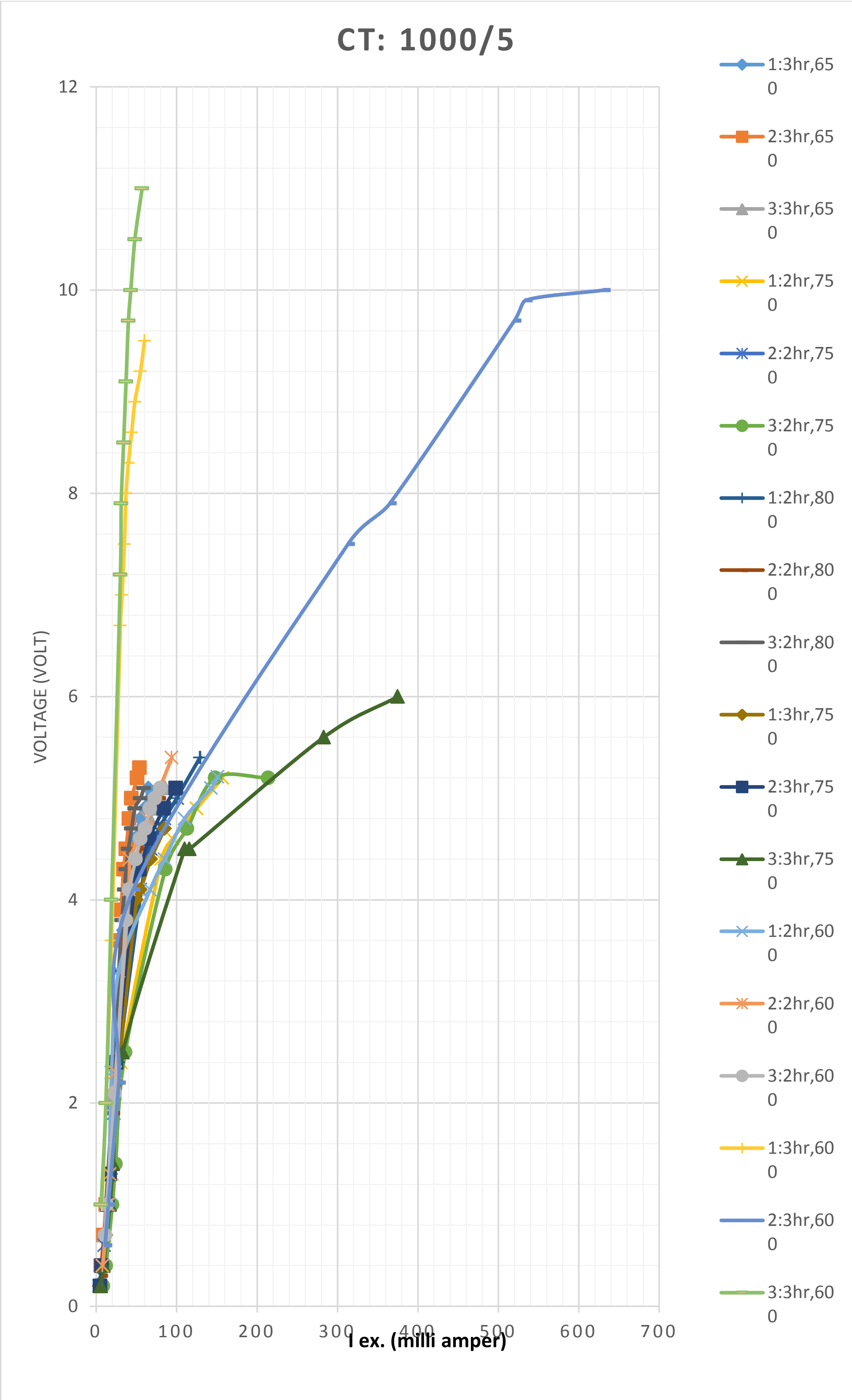


Figure 5.1 Voltage vs. Current graphs for 18 samples

From this Figure, it can see that, according to knee point determination, some samples exhibit good characteristics whereas some of them exhibit poor characteristics. Findings are tabulated in Table 5.1 with color codes green (best), yellow (convergent), and red (worst) to indicate the I-V characteristic. Table 5.1 also shows the numbering scheme we used for each sample.

Table 5.1 Temperature and time duration for each sample

| **No.** | **Sample** | **Group** |
|---|---|---|
| 1. | 600 ˚C – 3 hr | Best Results |
| 2. | 600 ˚C – 3 hr | |
| 3. | 650 ˚C – 3 hr | Convergent Results |
| 4. | 800 ˚C – 2 hr | |
| 5. | 650 ˚C – 3 hr | |
| 6. | 600 ˚C – 2 hr | |
| 7. | 600 ˚C – 2 hr | |
| 8. | 800 ˚C – 2 hr | |
| 9. | 650 ˚C – 3 hr | |
| 10. | 750 ˚C – 3 hr | |
| 11. | 800 ˚C – 2 hr | |
| 12. | 600 ˚C – 3 hr | |
| 13. | 750 ˚C – 3 hr | |
| 14. | 750 ˚C – 2 hr | |
| 15. | 600 ˚C – 2 hr | Worst Results |
| 16. | 750 ˚C – 2 hr | |
| 17. | 750 ˚C – 2 hr | |
| 18 | 750 ˚C – 3 hr | |

Each study groups are investigating in detail and the results given in the following sections.

## 5.1 Results

### 5.1.1 Results with Heat Treatment

Table 5.2 V, I values for six samples at 600°C/2h

| 1:2hr,600 | | 2:2hr,600 | | 3:2hr,600 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 5.21 | 151 | 5.4 | 94 | 5.1 | 80 |
| 5.1 | 143 | 4.8 | 64 | 5 | 73 |
| 4.8 | 110 | 4.4 | 42 | 4.9 | 67 |
| 4.4 | 85 | 4.1 | 41 | 4.7 | 61 |
| 4.1 | 67 | 2.3 | 24 | 4.6 | 55 |
| 3.3 | 28 | 1.3 | 17 | 4.4 | 49 |
| 2.3 | 19 | 1 | 14 | 4.1 | 41 |
| 1 | 15 | 0.4 | 8 | 3.8 | 37 |
| 0.4 | 8 | | | 2.1 | 23 |
| | | | | 1 | 13 |
| | | | | 0.7 | 11 |
| 4:2hr,600 | | 5:2hr,600 | | 6:2hr,600 | |
| V | I (mA) | V | I (mA) | V | I (mA) |
| 8.728 | 636 | 10.586 | 680.2 | 10.26 | 691.4 |
| 8.662 | 622 | 10.448 | 656 | 10.175 | 673.5 |
| 8.531 | 597.6 | 10.289 | 631.8 | 10.036 | 647.8 |
| 8.394 | 573 | 10.122 | 608.1 | 9.88 | 622.2 |
| 8.242 | 548 | 9.9348 | 584.6 | 8.67 | 462.2 |
| 7.13 | 404.2 | 8.2647 | 427.3 | 7.44 | 311.8 |
| 6.273 | 283 | 7.5183 | 336.8 | 7.404 | 293.4 |
| 3.516 | 52.29 | 4.149 | 47.47 | 4.086 | 52.22 |
| 1.951 | 30.4 | 2.2648 | 28.3 | 2.235 | 29.8 |
| 1 | 18.38 | 1 | 15.37 | 1 | 16.2 |
| 0.5997 | 12.58 | 0.674 | 11.55 | 0.6682 | 12.08 |
| 0.332 | 7.96 | 0.3674 | 7.178 | 0.3648 | 7.56 |
| 0.1843 | 4.969 | 0.2006 | 4.362 | 0.1995 | 4.68 |
| 0.102 | 3.116 | 0.1093 | 2.664 | 0.1089 | 2.92 |

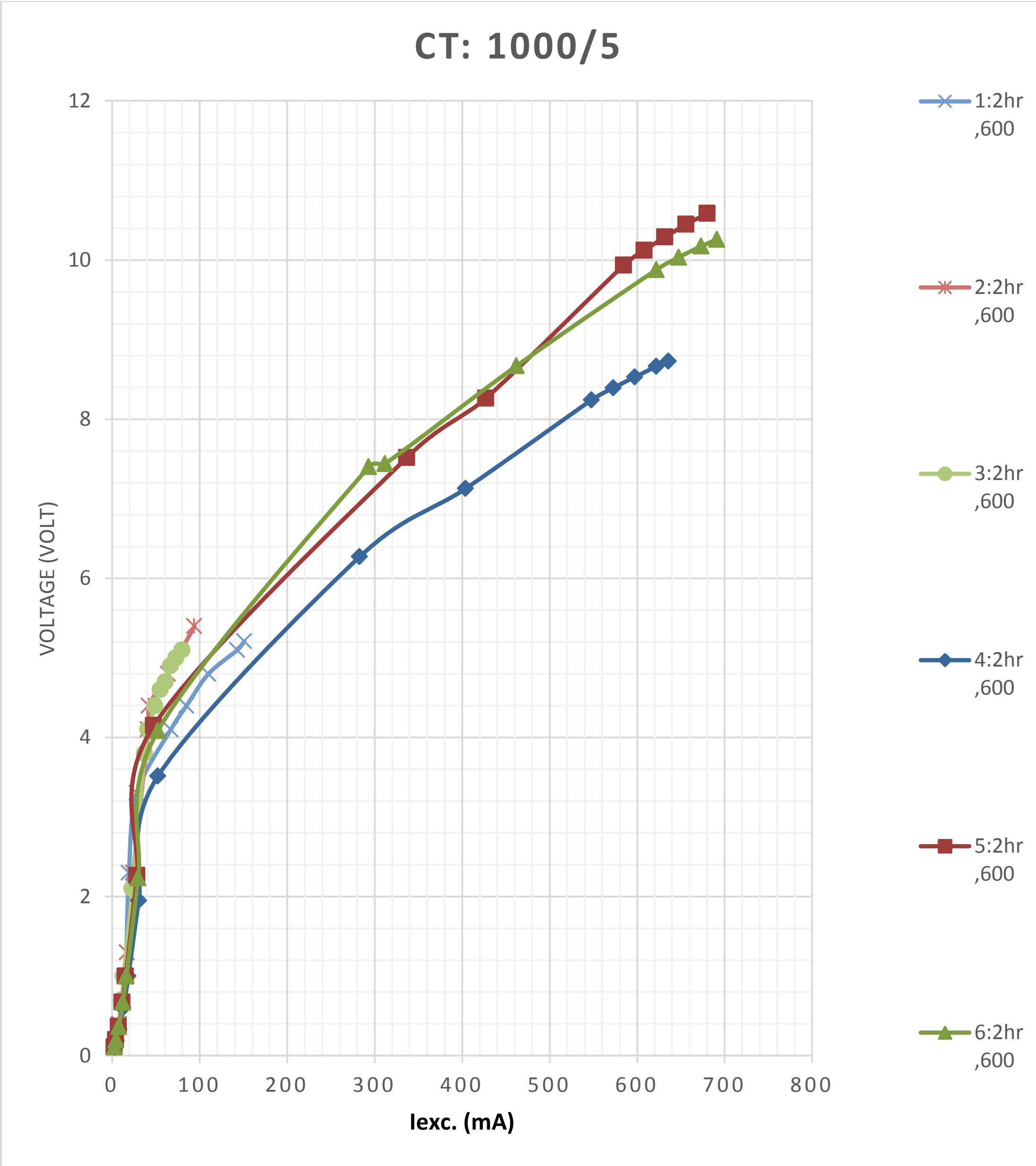



Figure 5.2 Voltage vs. current curve for six samples at 600℃/2h

Table 5.3 V, I values of three samples at 600°C/3h

| 1:3hr,600 | | 2:3hr,600 | | 3:3hr,600 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 9.5 | 60 | 10 | 631 | 11 | 57 |
| 9.2 | 55 | 9.9 | 534 | 10.5 | 48 |
| 8.9 | 48 | 9.7 | 520 | 10 | 43 |
| 8.6 | 44 | 7.9 | 365 | 9.7 | 40 |
| 8.3 | 40 | 7.5 | 313 | 9.1 | 37 |
| 8 | 37 | 4.1 | 46 | 8.5 | 34 |
| 7.5 | 35 | 2.2 | 28 | 7.9 | 31 |
| 7 | 32 | 1 | 15 | 7.2 | 30 |
| 6.7 | 30 | 0.6 | 11 | 4 | 19 |
| 3.6 | 19 | | | 2 | 12 |
| 2 | 12 | | | 1 | 6 |
| 1 | 7 | | | | |

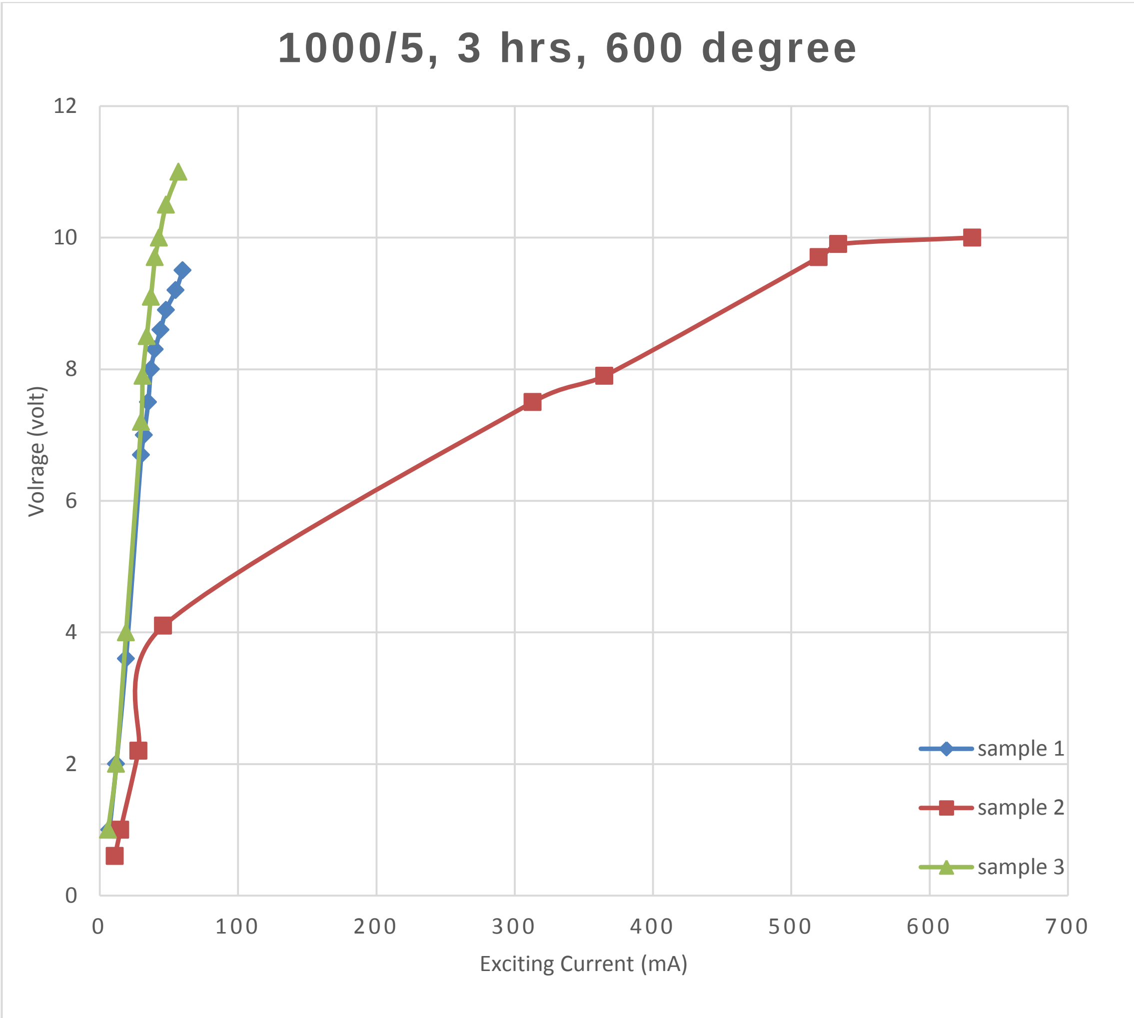



Figure 5.3 Voltage vs. current curve for three samples at 600°C/3h

Table 5.4 V, I values of three samples at 650°C/3h

| 1:3hr,650 | | 2:3hr,650 | | 3:3hr,650 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 5.1 | 65 | 5.3 | 54 | 5.1 | 86 |
| 4.9 | 60 | 5.2 | 51 | 5 | 80 |
| 4.8 | 55 | 5 | 44 | 4.9 | 73 |
| 4.6 | 48 | 4.8 | 41 | 4.8 | 67 |
| 4.4 | 44 | 4.5 | 37 | 4.6 | 61 |
| 4.2 | 40 | 4.3 | 34 | 4.5 | 57 |
| 4 | 37 | 3.9 | 31 | 4.1 | 47 |
| 3.7 | 34 | 3.6 | 30 | 3.7 | 38 |
| 3.6 | 33 | 2 | 20 | 2.1 | 23 |
| 2.1 | 21 | 1 | 12 | 1 | 13 |
| 1 | 13 | 0.7 | 9.3 | 0.7 | 10 |
| 0.7 | 10 | 0.4 | 6 | 0.4 | 7 |
| 0.4 | 6.6 | | | 0.2 | 4.7 |

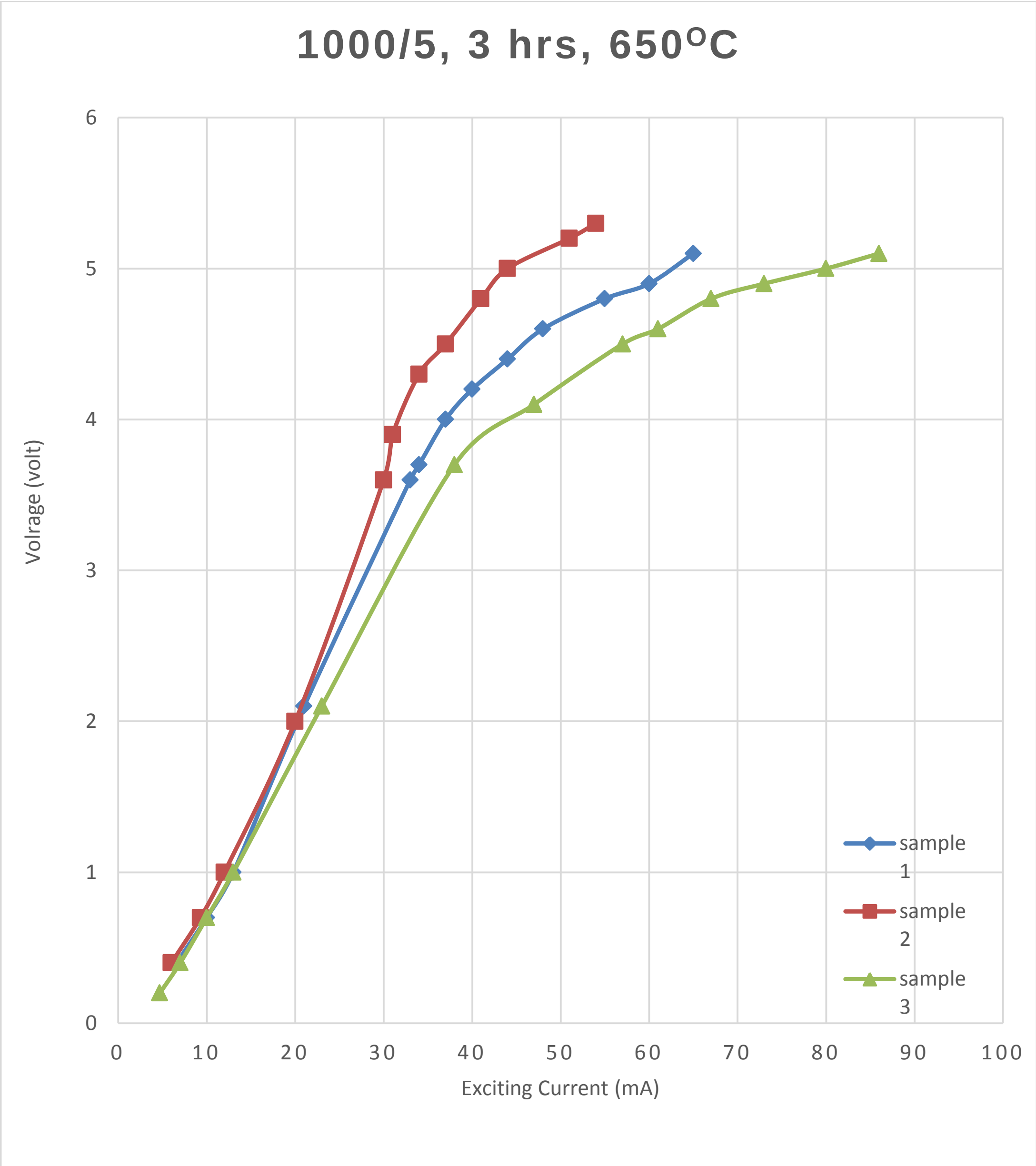



Figure 5.4 Voltage vs. current for three samples at 650℃/3h

Table 5.5 V, I values for three samples at 750°C/2h

| 1:2hr,750 | | 2:2hr,750 | | 3:2hr,750 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 5.2 | 157 | 5 | 101 | 5.2 | 214 |
| 4.9 | 125 | 4.8 | 85 | 5.2 | 148 |
| 4.6 | 95 | 4.5 | 68 | 4.7 | 113 |
| 4.4 | 81 | 4.1 | 55 | 4.3 | 86 |
| 2.4 | 31 | 3.8 | 44 | 2.5 | 36 |
| 1.3 | 20 | 3.5 | 36 | 1.4 | 24 |
| 1 | 16 | 3.4 | 36 | 1 | 20 |
| 0.4 | 8 | 1.9 | 22 | 0.4 | 12 |
| 0.2 | 5 | 1 | 14 | 0.2 | 8.6 |
| | | 0.6 | 10 | | |
| | | 0.3 | 6 | | |
| | | 0.2 | 4 | | |

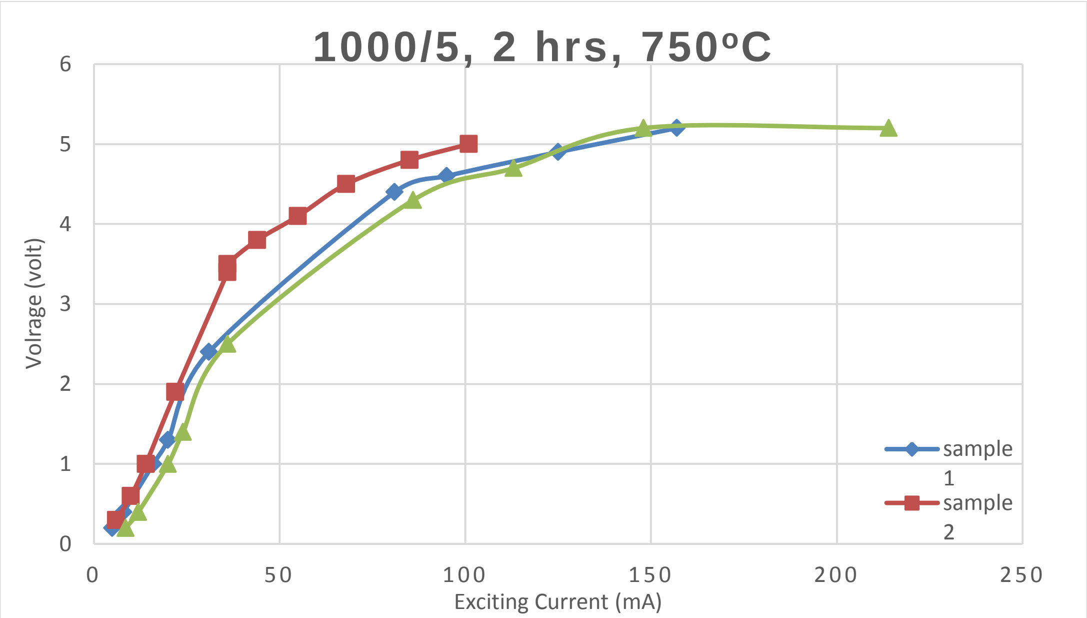



Figure 5.5 Voltage vs. current for three samples at 750°C/2h

Table 5.6 V, I values for three samples at 750°C/3h

| 1:3hr,750 | | 2:3hr,750 | | 3:3hr,750 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 4.7 | 85 | 5.1 | 99 | 6 | 375 |
| 4.4 | 68 | 4.9 | 84 | 5.6 | 283 |
| 4.1 | 55 | 4.6 | 66 | 4.5 | 116 |
| 4 | 50 | 4.3 | 54 | 4.5 | 110 |
| 2.2 | 26 | 4.3 | 50 | 2.5 | 33 |
| 1 | 15 | 2.4 | 25 | 1.4 | 21 |
| 0.7 | 12 | 1.3 | 17 | 1 | 17 |
| 0.4 | 7 | 1 | 14 | 0.4 | 9 |
| 0.2 | 4 | 0.4 | 7 | 0.2 | 6 |

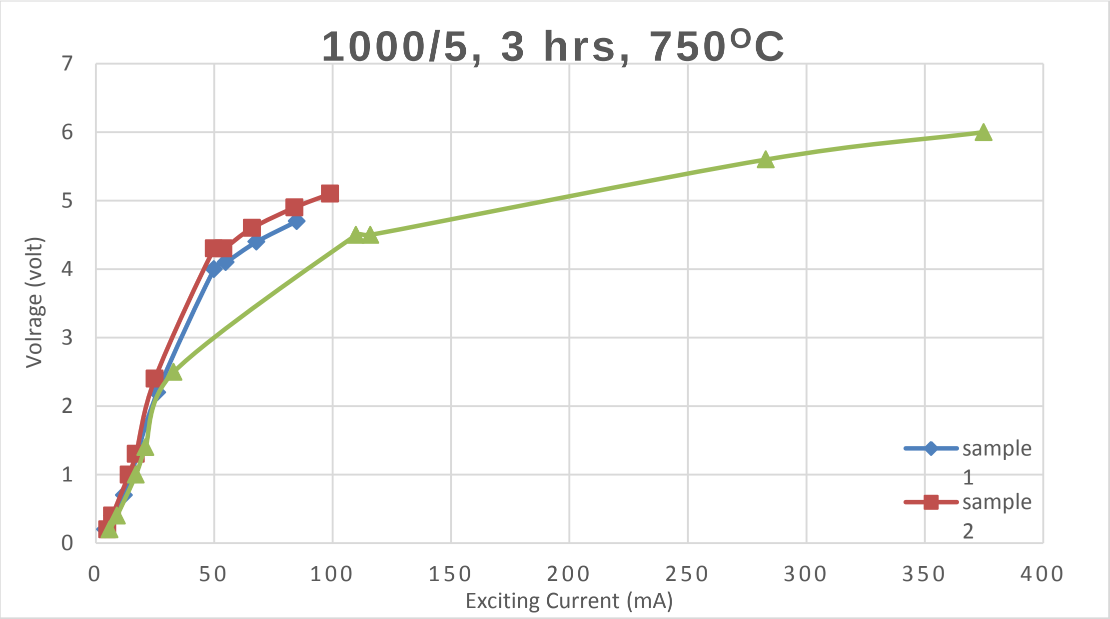



Figure 5.6 Voltage vs. current curve for three samples at 750°C/3h

Table 5.7 V, I values for three samples (1, 2, 3) at 800°C/2h

| 1:2hr,800 | | 2:2hr,800 | | 3:2hr,800 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 5.4 | 130 | 5 | 77.9 | 5.1 | 59.1 |
| 5.4 | 129 | 4.9 | 68.3 | 5 | 55 |
| 5 | 100 | 4.5 | 55 | 4.9 | 48 |
| 4.7 | 78 | 4.2 | 44 | 4.7 | 44 |
| 4.4 | 62 | 3.8 | 38 | 4.5 | 40 |
| 2.4 | 28 | 3.4 | 33 | 4.3 | 37 |
| 1.3 | 19 | 1.9 | 21 | 4.1 | 35 |
| 1 | 15 | 1 | 13 | 3.8 | 32 |
| 0.4 | 8.2 | 0.6 | 10 | 3.3 | 28 |
| | | 0.3 | 6 | 1.9 | 19 |
| | | | | 1 | 12 |

Table 5.8 V, I values for three samples (4, 5, 6) at 800°C/2h

| 4:2hr,800 | | 5:2hr,800 | | 6:2hr,800 | |
|---|---|---|---|---|---|
| V | I (mA) | V | I (mA) | V | I (mA) |
| 8.464 | 63.49 | 6.784 | 70.33 | 7.41 | 71.9 |
| 8.036 | 54.98 | 6.608 | 64.63 | 7.24 | 66.9 |
| 7.746 | 48.65 | 6.4125 | 59.24 | 7.039 | 61.37 |
| 7.428 | 44.64 | 6.202 | 54.3 | 6.818 | 56.39 |
| 7.064 | 41.28 | 5.931 | 47.63 | 6.5865 | 49.68 |
| 5.868 | 33.58 | 5.7485 | 43.85 | 6.348 | 45.9 |
| 3.276 | 21.47 | 5.27 | 37.45 | 6.086 | 42.1 |
| 1.829 | 14.37 | 4.909 | 34.63 | 5.825 | 39 |
| 1 | 9.22 | 2.785 | 21.63 | 5.296 | 35.01 |
| 0.5698 | 5.98 | 1.58 | 14.8 | 3.0145 | 22.04 |
| 0.3179 | 3.82 | 1 | 10.64 | 1.715 | 15.3 |
| 0.1774 | 2.4 | 0.5082 | 6.397 | 1 | 10.32 |
| | | 0.288 | 4.11 | 0.555 | 6.61 |
| | | 0.1633 | 2.66 | 0.315 | 4.27 |
| | | 0.0925 | 1.766 | 0.179 | 2.78 |
| | | 0.05238 | 1.2 | 0.102 | 1.842 |
| | | 0.0296 | 0.8512 | | |
| | | 0.01669 | 0.6289 | | |

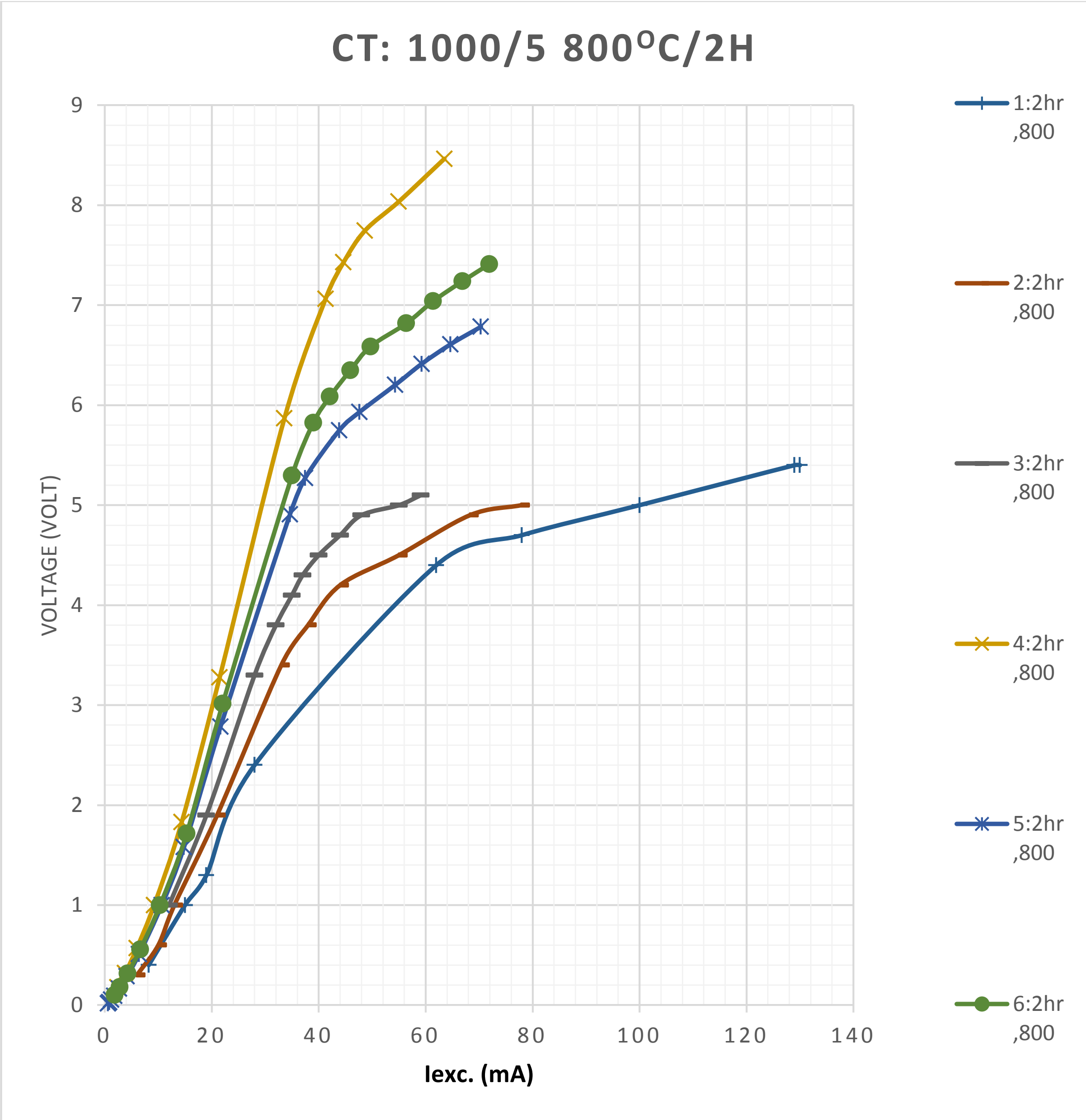



Figure 5.7 Voltages vs. current curve for six samples at 800°C/2h

### 5.1.2 Results without Heat Treatment

Table 5.9 V, I values for three samples without heat treatment

| 1:no heat treat | | 2:no heat treat | | 3:no heat treat | |
|---|---|---|---|---|---|
| V | I (\|ma) | V | I (\|ma) | V | I (\|ma) |
| 3.6911 | 75 | 3.709 | 75 | 3.79 | 71.9 |
| 2.11 | 36.4 | 2.119 | 36.2 | 2.26 | 34.9 |
| 1 | 20 | 1.002 | 19.9 | 1 | 18.4 |
| 0.639 | 14.5 | 0.6413 | 14.4 | 0.681 | 14 |
| 0.353 | 9.32 | 0.354 | 9.255 | 0.375 | 8.96 |
| 0.1958 | 5.8 | 0.196 | 5.79 | 0.207 | 5.58 |
| 0.1083 | 3.6 | 0.108 | 3.57 | 0.1142 | 3.44 |
| 0.05985 | 2.27 | 0.0599 | 2.25 | | |
| 0.033 | 1.47 | 0.033 | 1.45 | | |
| 0.0181 | 0.981 | 0.0181 | 0.97 | | |

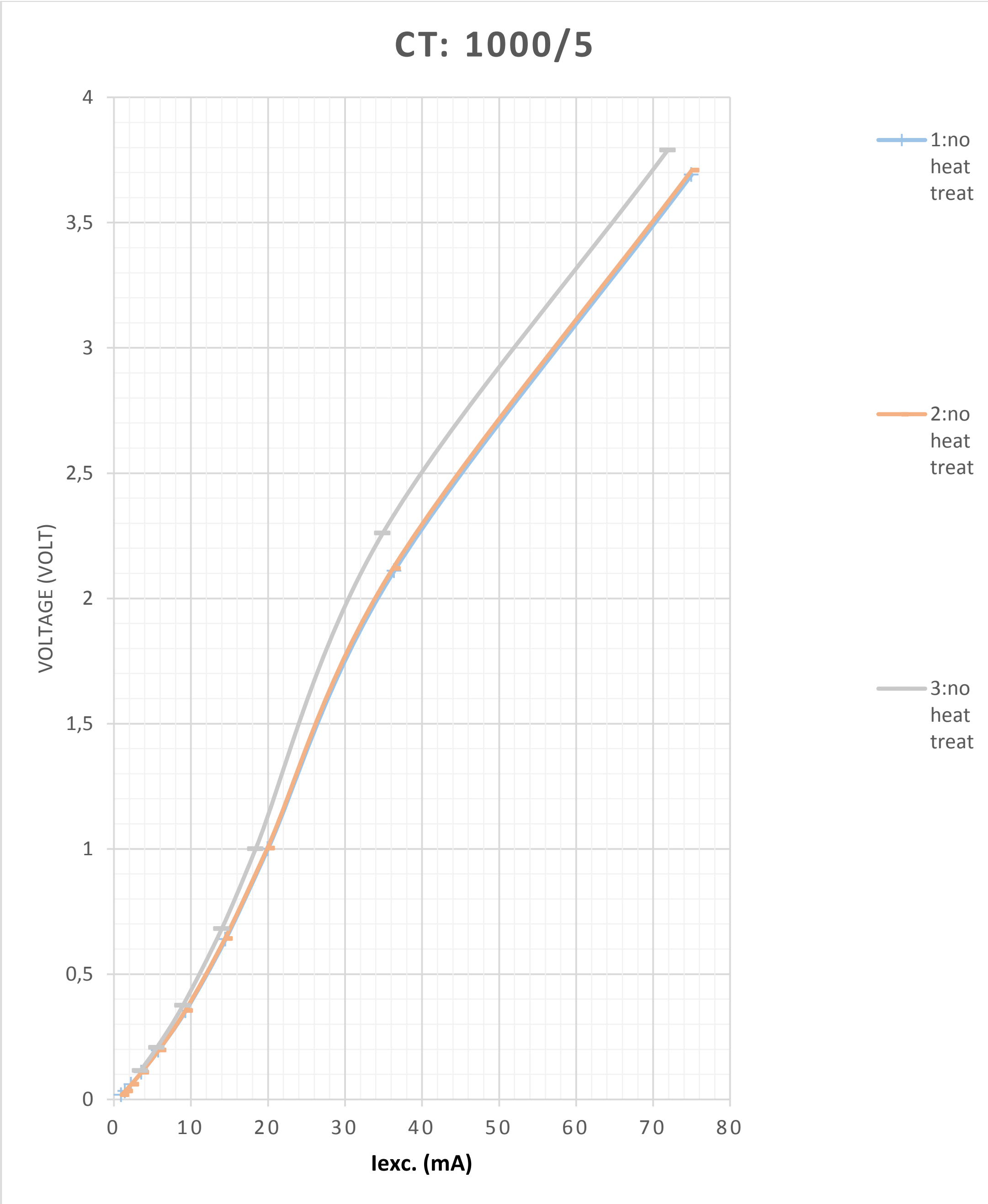



Figure 5.8 Voltage vs. current graphs for three samples without heat treatment

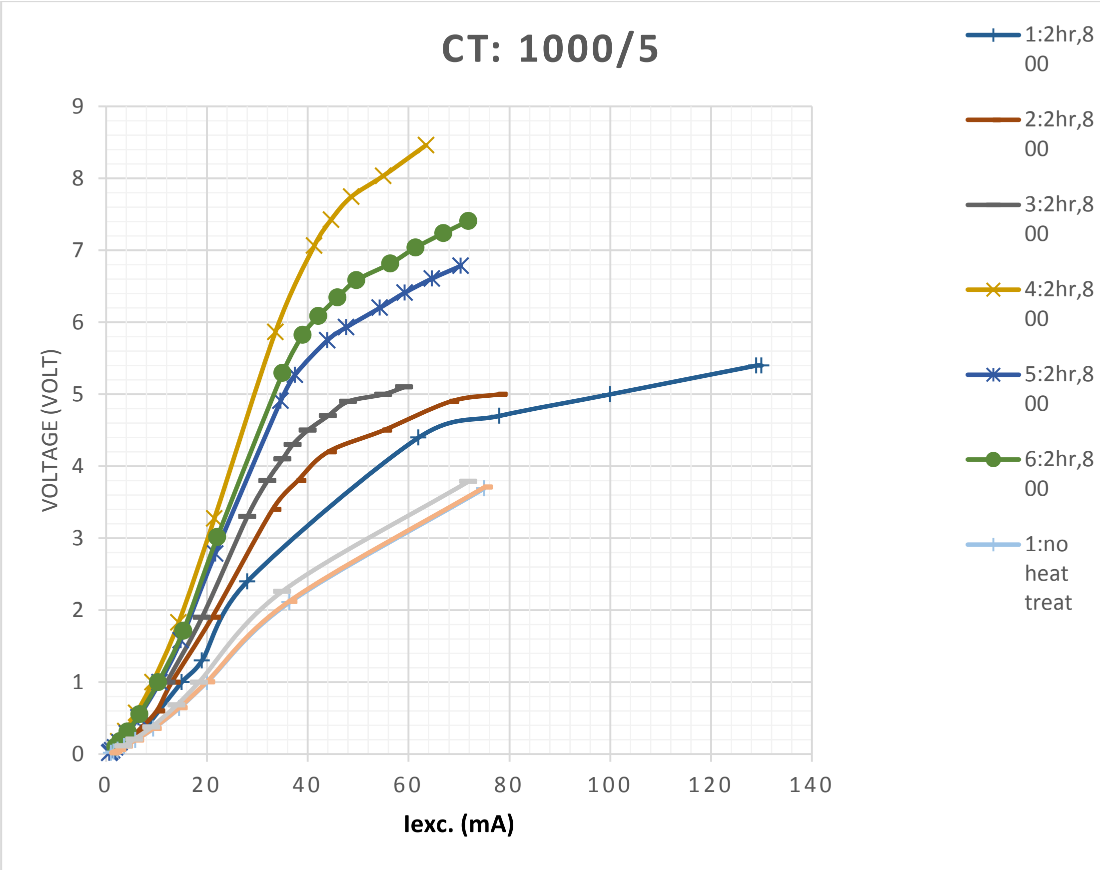



Figure 5.9 Voltage vs. current graphs for three samples without heat treatment and for samples with heat treatment with good magnetic properties.

## 5.2 Discussion

After conducting the analysis, using OMICRON CT device some important data can be deducing for classification of the performance of the transformer, regarding accuracy and class for the transformer and by determining the values of exciting current, which correspond the voltage values on both ends of the secondary coil.

These processes were doing to plot the saturation (induction) curve or (I–V) curve to identify the performance of the transformers.

After determining the previously mentioned data for 18 samples, the saturation curve was plot for every sample in comparison with the samples that hold the same design and same cycle at the same time. The plot gives the curve for every group to identify which heat cycle it release the stress and at any time period needed for that process. This will give agreeable results to improve the stress relieve, which accordingly enhances the magnetic properties for the iron core. This, in turn, improves the transformer's performance and allowing them to pass all the standard tests of IEC 60044-1.

By comparing the curves one can identify so-called the knee point for every sample. The knee point is define as the point at which the voltage increase is too little in terms of terms of voltage on the secondary coil, when compared with the quick current increase when the percentage of increase exceeds 50% in the exciting current compared with a percentage of increase of 10% in the voltage of the secondary coil. This called the stage of saturation. For example

If $V_S$ =10 volt, $I_{exc}$=50 mA

10×10% = 1 volt, 1+10=11 volt, 50×50%=25mA, 50+25=75mA

In this example, if $I_{exc}$ exceeds 75mA, this means that the transformer will enter the stage of saturation, which means its failure. This property depends on multiple reasons such as:

- shape of the iron core,
- type of wire in the secondary coil,
- classification of transformer,
- accuracy of transformer,
- electrical circuits that surrounding the transformer,
- Process of heat treatment (stress relief), it is successful or not.

The knee point can be determined by calculating the voltage of the secondary coil is operating voltage by the following equation:

$$V_S = \left[\frac{VA}{I} + I_S \times R_{75°\text{C}}\right] \times 120\% \qquad (5.1)$$

Where $R_{75°\text{C}}$ is the resistance of the secondary coil at 75℃, which is taking from the analysis device OMICRON CT and called voltage drop. In the tested samples, it found that:

$$V_S = \left[\frac{15}{5} + 5 \times 0.1\right] \times 120\% = 4.2\text{V}$$

From this value, it can found that the extension of the transformers at which the exciting current is more than 50mA is within the saturation zone.

From the previously mentioned information with the comparison regarding (I-V) curve it can be concluded that all the transformers passed the test successively with a disparity in the success data regarding that there was a heat treatment cycle at which acceptable result have been achieved with 600℃ / 3 h as shown in Figure (5.3). When the value of voltage for the secondary coil is doubled, the transformer will not enter to the saturation zone, therefore, resulting in magnetic properties for the iron core for a high quality transformer. This result shows that without using a noble gas, which prevents oxidation and the existence of gas repellent device (ignition and oxidation) like oxygen, heat treatment process by using electronic furnace that has multiple sections working with multiple temperatures can produce desired common effects desired.

This study shows that heat treatment temperature can be minimize for stress relief with identifying the treatment time with simple ambient conditions. This was doing with low cost leading to minimizing costs of producing this iron core. Consequently, this also minimizes the production cost of the high quality and high accuracy transformers concerning varying ratio of transforming and conditions of operation.

It is also possible to compare the results of transformers that have undergone heat treatment with the results of transformers with that have not undergone heat treatment. It possible to see the difference in the results, as shown in Figure (5.8) and Table 5.9, the curve of transformers without heat treatment are under the curve of transformers with heat treatment. This shows that non-thermally treated transformers intervention saturation zone early before the operating voltage.

## 5.3 Conclusions

The samples that have been treating for longer time and at low temperatures showed the best results for stress relief. This could attribute to those high temperatures that led to the damage of electrical insulation allowing eddy currents to generated, which ultimately reduces the magnetic properties.

It is known that the temperature limits for stress-relief for electrical steel ranges between 1400 to 1550˚F (760 to 845˚C), but it was noticed that using induction furnace (batch furnace) at 600˚C for 3 hours gave the best results. Therefore, it concluded that samples heated at natural atmosphere with low temperatures and longer time is better than raising the temperature and reducing the time.

Short time (2 hours) at 600˚C was not sufficient to relieve mechanical stress for electrical steel.

Irregularities of some results could be attributing to oxidation and accumulation of carbon on the iron core edges, which could cause deterioration of magnetic properties.

Hence, the emphasis in literature on conducting stress-relief process under vacuum or with gases that do not cause oxidation.

When interpreting the results from this study another important aspect that must be taking into consideration is that, the temperature usually not distributed evenly inside the batch furnace.

## 5.4 Future Work

In this study, we performed an experiment to identify heat treatment cycle (temperature and time duration) for electrical iron cores in current transformers by using a batch (inductance) furnace.

Our analysis with OMICRON CT Analyzer allowed us to select the best cycle. It will be extremely useful, however, to inspect the crystal structure of the steel after the heat treatment cycle. A following study is planning to investigate the crystal structure and its relation to the enhanced magnetic properties of the electrical steels manufactured in this study.

Another study will performed by using continuous furnace with noble gas and vacuum furnace with the same cycles outlined in this thesis. New results will be comparing with data from this thesis.

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## PUBLISHMENTS

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