Analysis and Application of Maxwell's Equation for Induction Heating

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***Abstract* —** *This article involves the development of the Maxwell equations considering a induction heating system. It is analyzed by computer program "Ansys Maxwell," to observe the development of the magnetic field. The system is composed of an induction heating machine where it will be generating a 30(amp) of current to a coil of copper. The induced system is a cylinder of graphite. It was observed by the mentioned program and the behavior of the electromagnetic field. This shows that within the area of the cylinder if the phase angle is maintained at about 90 degrees, the magnetic flux lines generated by the coil maintain symmetry and a magnetic field increasing the current density at 2.4365x10 ^ 3 ª / m ^ 2. We know that if the current density also increases its temperature increases thereby bringing the internal area of the cylinder to very high temperatures.*

Key Terms *— Electromagnetic Field, Induction Heating, Numerical Modeling, Thermal Field.*

INTRODUCTION

The induction heating system is one of the most innovative systems in manufacturing companies, is a convenient method useful for local heat treatment. The induction can be used in different forms. In the development of the article we will see more about it, but first we have to know a little about Electromagnetic Induction. The Electromagnetic induction is the production of a potential difference (voltage) across a conductor when it is exposed to a varying magnetic field. It is the basis of all induction heating, was discovered by Michael Faraday in 1831[1]. For nearly hundred years, this principle was used in motors, generators, transformers, radio communications, etc. The Induction heating is the process of heating an electrically conducting object by electromagnetic induction, where eddy currents are generated within the metal and resistance leads to Joule heating of the metal. An induction heater consists of an electromagnet, through which a high-frequency alternating current (AC) is passed. Heat may also be generated by magnetic hysteresis losses in materials that have significant relative permeability. The frequency of AC used depends on the object size, material type, coupling and the penetration depth. The alternating current heating inductor generates an electromagnetic field that creates an electric current in the workpiece. This circulating current moves against the resistivity of the material and generates heat. (see Figure1).[2]

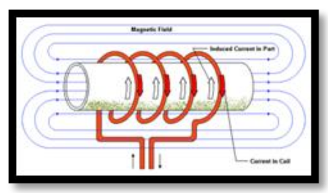

Figure 1
Electromagnetic Field Example in a Induction Heating Process

Induction heating is a method for continuous and rapid heat for industrial applications to be welded or alter the properties of metals or other electrically conductive materials. The process uses electrical currents induced in the material to produce heat. Although the basic principles of induction are well known, recent advances in solid state technology have greatly simplified induction heating, making it a very cost-effective heating method for applications involving joints, treatment, heating and materials testing.

APPLICATIONS

Production rates can be maximized because induction works so quickly; heat is developed directly and instantly (>2000 F. in <1 second) inside the part [2]. This advantage allows us to carry out various applications such as, induction coils, Temple by induction, tempered by induction, induction brazing, curing, welding, normalized, pre-heating, post-heating, forging, Fusion by induction and many techniques of induction that have been developed as the technology progresses. Induction heating allows the targeted heating of an applicable item for this applications.. Iron and its alloys respond best to induction heating, due to their ferromagnetic nature. Induction heating has been used to heat liquid conductors and also gaseous conductors such as gas plasma. Induction heating is often used to heat graphite crucibles containing other materials and is used extensively in the semiconductor industry for the heating of silicon and other semiconductors. That's one of the purposes of this paper, the fusion by induction and which we will be analyzing as this paper in its development. Utility frequency (50/60 Hz) induction heating is used for many lower cost industrial applications as inverters are not required.

ELEMENTS THAT COMPOSE AN INDUCTION HEATING

The basic elements of an induction heating system are alternating current generator, an inductive coil and the workpiece (see Figure 2). The generator sends alternating current through the coil, generating a magnetic field. When placing the workpiece on the coil, the magnetic field induces eddy currents in the workpiece (see Figure 1), precise amounts of heat generating clean, located, without any physical contact between the coil and the workpiece.(see Figure 2).

Figure 2
Induction Heating Machine

OBJECTIVE

Analyzing a induction heating system we want to develop Maxwell's equations and simulate what is happening on the piece when it is induced. For this Ansys Maxwell, Solidwork and Quick Field programs are used. The objective of this paper consist open the possibility of new projects to reduce the costs involved in the process of casting metal and semi-metallic materials.

DEVELOPMENT OF THE MAXWELL EQUATIONS

Around 1860, the great Scottish physicist James Clerck Maxwell deduced experimental laws of electricity and magnetism (laws Coulomb, Gauss, Biot-Savart, Ampere and Faraday) could be summarized in a concise mathematical form is now known as Maxwell's equations [3]. Coming explain where they exit and its relation with the Paper.

MAGNETIC FIELD

The magnetic field whose direction is perpendicular to the plane of the loop, varies with time in a way [1]:

$$B=B_0 \text{ sen}(w\, t) \quad (1)$$

For the Equation (1) see Figure 3[1]. The flow of a magnetic field across a surface is given by Equation (2);

$$\phi_m = \int_S \vec{B}\cdot\hat{n}\,dA = \int_S \vec{B}\cdot d\vec{A} = \int_S B_n\,dA \quad (2)$$

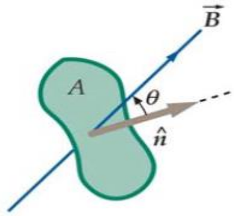

Figure 3
Surface Representative Diagram

For a coil of N turns and a uniform field the Equation (3) represent it and Equation (4) if:

$$\phi = NB \cdot S = NBS \cdot sen(wt) \quad (3)$$

$$\phi = NB \cdot \hat{n}A = NBA\cos\theta \quad (4)$$

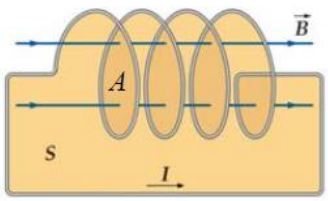

Figure 4
Coil Circuit Representation

The Figure 4[4] represents the coil. When the current changes induced current appears as if there is a source of electromotive force (emf). The emf induced depends on the rapidity of change of the magnetic field flux with time. According to Faraday's law Equation (5), the mathematical expression is given by [5];

$$\varepsilon = -\frac{d\phi_m}{dt} \quad (5)$$

Thus;

$$V_\varepsilon = -\frac{d\phi}{dt} \quad (6)$$

The emf is induced in the coils by Equation (7) when the V_s is calculate by Equation (6);

$$V_E = -\frac{d\phi}{dt} = -SNB_0\omega\cos(\omega t) \quad (7)$$

MAXWELL EQUATIONS

The electromagnetic field is described by a system of equations complied by Maxwell [1]-[2]:

Gauss Law in Equation (8),

$$\oint_S \vec{E} \cdot d\vec{A} = \oint_S E_n dA = 4\pi k Q_{\text{int}} \quad (8)$$

Gauss Law for magnetism in Equation (9);

$$\oint_S \vec{B} \cdot d\vec{A} = \oint_S B_n dA = 0 \quad (9)$$

Faraday Law (without movement) in the Equation (10) depends to the Area:

$$\int_C \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\oint_S B_n \cdot dA = -\int_s \frac{\partial B_n}{\partial t} dA \quad (10)$$

Ampere's law generalized:

$$\int_c \vec{B} \cdot d\vec{l} = \mu_0(I + I_d) = \mu_0 I + \mu_0\varepsilon_0 \frac{d\phi_0}{dt} \quad (11)$$

Where Ampere's law we saw in the previous Equation (11) (valid for stationary power) is added to the term of the Maxwell displacement current, to include all situations [6].

SOLIDWORKS DESIGN

As mentioned above, we are analyzing an induction system, for this we represent what is the design with such parts. In this case, the cylinder will be the induced material will be an existing graphite cylinder which will be joined to a coil to create representative electromagnetism. A design was created in solidworks this program has been including the coil and cylinder.(see Figure 5).

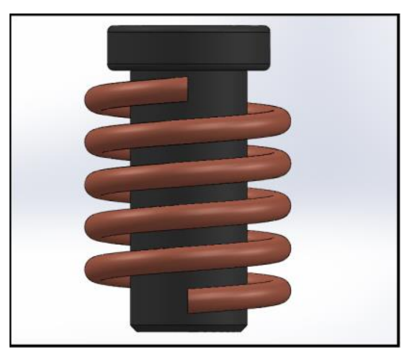

Figure 5
Induction Coil with Cylinder

The graphite cylinder was analyzed in solidworks (see Figure 6) to verify their generic reaction for a thermal simulation.

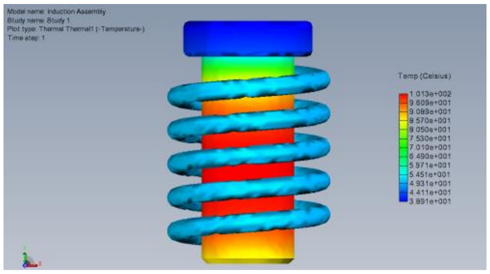

Figure 6
Graphite Cylinder in Solidworks with a General Thermal Simulation

With Quick Field program creates a representation of a coil segment and part of the cylinder. With this we can appreciate the generation of electromagnetism when an electrical charge is applied. (see Figure 7, 8, 9)

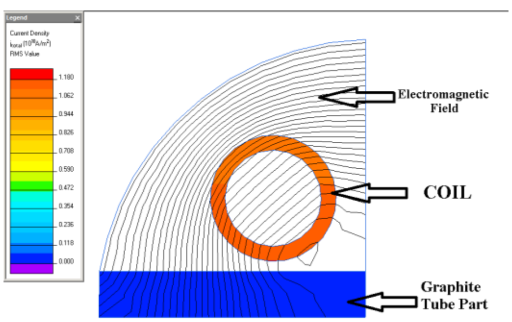

Figure 7
Electromagnetic Field Generated by Quick Field Program Student Version

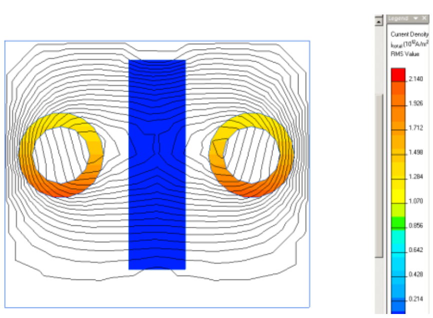

Figure 8
Electromagnetic Field

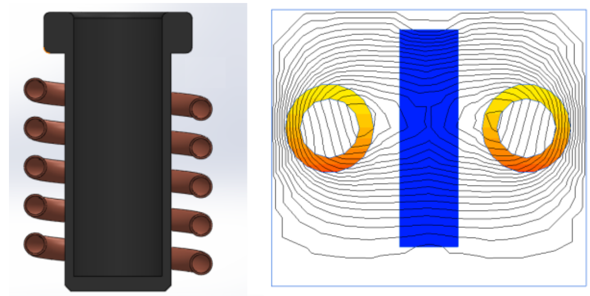

Figure 9
Segment Area Comparison

THEORETICAL ANALYSIS

Ansys Maxwell software is used to measure the electromagnetic flux generated by the following; an induction machine that is generating a current of (30 – 50) amps (Figure 2) to a copper coil represented in Figure 5.

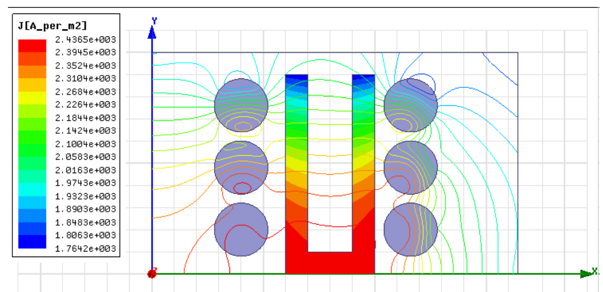

Figure 10
The Magnetic Flux lines and Current Density in the Cylinder Phase of 90 deg.

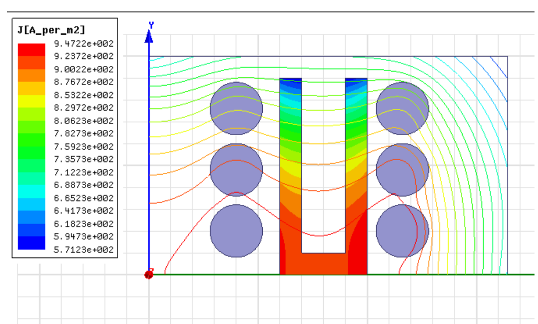

Figure 11
Magnetic Flux lines and Current Density with Cylinder Phase of 45 deg.

In the middle of this is a cylinder of graphite. It is with a current density of copper 0.000010323m ^ 2 and a current of 50amp. In Figure 11 we see the lines of flux generated by the magnetic flux, but having a phase angle of 45 degrees cannot appreciate symmetry and therefore the current density is lower in the inner area. In Figure 10 the phase angle is 90 degrees generating a symmetrical magnetic flux reaching a current density greater in the center area. Having a higher current density we can obtain a higher temperature. Next we explain the relationship between these.

ELECTROMAGNETIC AND THERMAL ANALYSIS

The electromagnetic field is described by a system of equations complied by Maxwell [7]. A electromagnetic Analysis Diagram is represented in the Figure 12[8]. The development of Gauss Law, Faraday's Law and Ampere's Law are detailed in a circuit analysis as occurs in a electromagnetic problem.

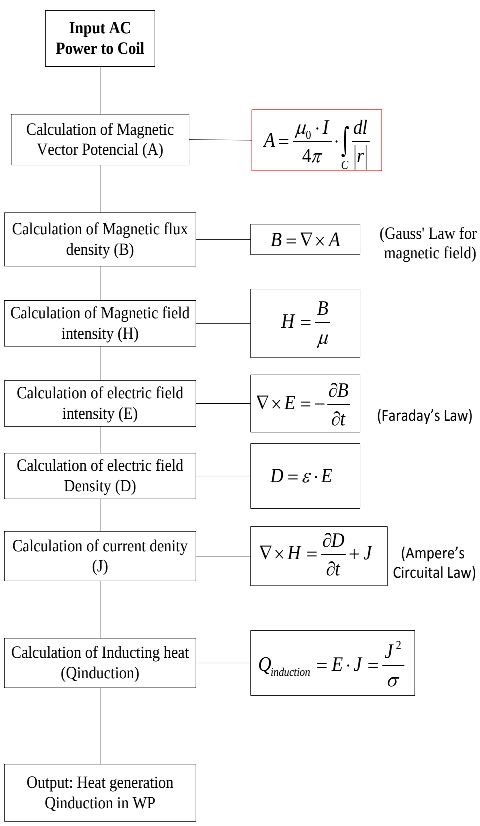

Figure 12
Electromagnetic Analysis Maxwell Diagram

THERMAL ANALYSIS WITH FINITE ELEMENT MODEL

A finite element analysis Figure 13 is developed to represent a specific element section and explain the relation between electromagnetic and thermal.

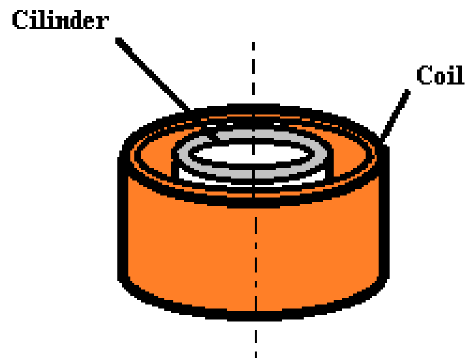

Figure 13
Section of the Finite Analysis

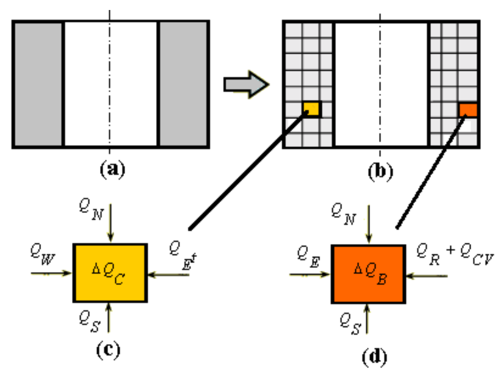

Figure 14
Finite Element Model

(a) Cylindrical Geometry (b) FEA Model (c) Interior Element (d) Surface Element

For the heat conduction Q represented in Figure 14[4] the Equation (12) is developed:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = k \cdot \nabla^2 T + Q_{induction} \quad (12)$$

With the Induced joule heat, Heat radiation and Heat convection we obtain Equation (13)[9]:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = k \cdot \nabla^2 T + Q_{induction} - A \cdot \sigma \cdot \varepsilon \cdot F \cdot (T^4 - T_{air}^4) - A \cdot h \cdot (T - T_{air}) \quad (13)$$

ANSYS SIMULATION RESULTS

Using ANSYS Mechanical generate 2D cylinder conditions along with the coil. Figure 15 shows the flow lines of the magnetic field where they pass right through the cylinder as the magnetic generation of graphite is low and not reject this. The inside of the cylinder should show a concentration in the magnetic field as see in Figure 16. The magnetic field vector show in Figure 16 is related to the density of current applied to the coil. Figure 17 shows the magnetic density giving a higher value of 345 x10-11 and a maximum recorded 388 x10-11 on the inside of the cylinder.

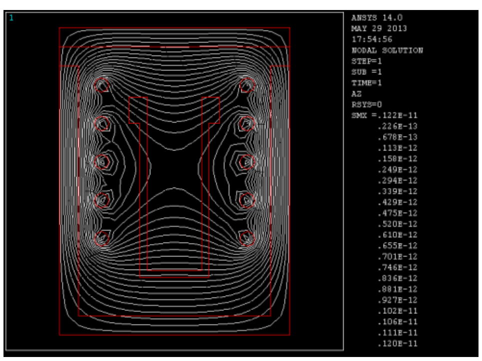

Figure 15
Magnetic Flux Lines

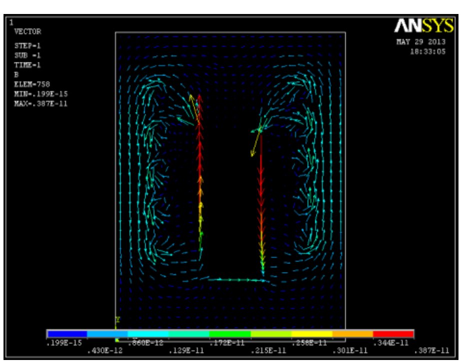

Figure 16
Magnetic Vector

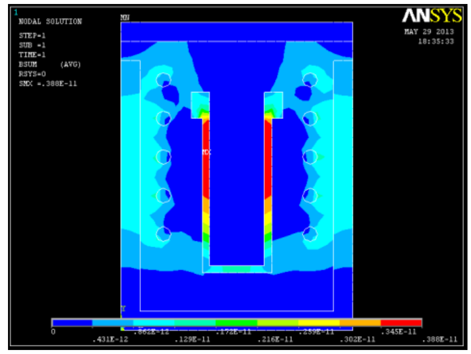

Figure 17
Magnetic Flux Density

CONCLUSION

Faraday's Law states that a variable magnetic field in time causes the appearance of an electric field no conservative. In the presence of a conductive medium the electric field gives rise to induced currents, the induced emf is proportional to the rate of change of magnetic field flow. Faraday's Law can also be used to calculate induced currents in moving conductors within static magnetic fields: motion fem. About the induced currents, are forces due to its own magnetic field that creates them, these forces oppose changing magnetic flux. As we have seen in Figure 11 and 12, a change in the degree of phase may be crucial to change the symmetry of the magnetic field. So we get a current density of 9.4722x10 ^ 2 to 45 degrees, unlike 2.4365x10 ^ 3 to 90 degrees. An inductor or coil, can store magnetic energy. The laws of electricity and magnetism are summarized by Maxwell's equations, which imply that 45 and 90 degrees of phase tend to an orientation in the field. According to the development of these and finite element analysis can appreciate the relationship between the electromagnetic field on a cross sectional area and thermal field. Observing the graph obtained and this relationship we can say that the area of the table marked shows the current density and the amount of temperature to be increased to obtain the high temperatures inside the cylinder.

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