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DESIGN AND CONSTRUCTION OF A MAGNETIC INDUCTION HEATING SYSTEM

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بسم الله الرحمن الرحيم

Abstract :

Induction heating is a clean, efficient, and rapid method of heating electrically conductive materials using electromagnetic fields. This project presents realization, the complete design, simulation, and experimental validation of a low-voltage magnetic induction heating system based on a Zero Voltage Switching (ZVS) inverter operating at 12V. The objective was to investigate the thermal response of various steel objects when exposed to a resonant electromagnetic field generated by a custom-designed induction coil. The project included theoretical grounding in electromagnetic principles, detailed system architecture development, component selection, and implementation of safety and control mechanisms. Experimental results demonstrated successful heating of various ferromagnetic materials with controlled power input and measurable thermal efficiency. Simulations performed in MATLAB/Simulink confirmed resonance operation and high current generation, validating theoretical predictions.

Key Words: Induction heating, electromagnetic induction,MATLAB simulation.

Résumé:

Le chauffage par induction est une méthode propre, efficace et rapide de chauffage de matériaux conducteurs d'électricité par champs électromagnétiques. Ce projet présente la réalisation, la conception complète, la simulation et la validation expérimentale d'un système de chauffage par induction magnétique basse tension basé sur un onduleur à commutation de tension nulle (ZVS) fonctionnant à 12 V. L'objectif était d'étudier la réponse thermique de divers objets en acier exposés à un champ électromagnétique résonant généré par une bobine d'induction sur mesure. Le projet comprenait l'approfondissement théorique des principes électromagnétiques, le développement détaillé de l'architecture système, la sélection des composants et la mise en œuvre de mécanismes de sécurité et de contrôle. Les résultats expérimentaux ont démontré le chauffage réussi de divers matériaux ferromagnétiques avec une puissance d'entrée contrôlée et un rendement thermique mesurable. Les simulations réalisées sous MATLAB/Simulink ont confirmé le fonctionnement en résonance et la génération de courant élevé, validant ainsi les prédictions théoriques.

Mots clés: Chauffage par induction, induction électromagnétique,simulation MATLAB.

ملخص:

التسخين الحثي طريقة نظيفة، فعّالة، وسريعة لتسخين المواد الموصلة للكهرباء باستخدام المجالات الكهرومغناطيسية. يقدم هذا المشروع تصميمًا كاملاً، ومحاكاة، واختبارًا تجريبيًا لنظام تسخين حثي مغناطيسي منخفض الجهد، يعتمد على عاكس تحويل جهد صفري يعمل بجهد 12 فولت. كان الهدف دراسة الاستجابة الحرارية لمختلف الأجسام الفولاذية عند تعرضها لحقل كهرومغناطيسي رنيني ناتج عن ملف حثي مصمم خصيصًا. تضمن المشروع أسسًا نظرية لمبادئ الكهرومغناطيسية، وتطويرًا مفصلًا لبنية النظام، واختيار المكونات، وتطبيق آليات السلامة والتحكم. أظهرت النتائج التجريبية نجاح تسخين مختلف المواد المغناطيسية الحديدية باستخدام مدخلات طاقة متحكم بها وكفاءة حرارية قابلة للقياس. أكدت عمليات المحاكاة التي أُجريت في المحاكاة فعالية الرنين وتوليد تيار عالي، مما أثبت صحة التنبؤات النظرية.

الكلمات المفتاحية:

التسخين الحثي، الحث الكهرومغناطيسي، المحاكاة.

Dedication

My time at university is over after a long and difficult trip.

here I am finishing my final thesis with full energy.

I dedicate my degree and my happiness to ***(My beautiful mother)***

Shine bright like a diamond

The kind heart ***(My dear father)***

Men create men, and you taught me to be a man.

my aunts,my family, friends,and teachers.

I want to thank me for believing in me. I want to thank me for doing all this hard work. I want to thank me for having no days off. I want to thank me for trying to do more right than wrong. I want to thank me for being me at all times.

Thank you.

ELMONTASSER BIALLAH.

Dedication

My academic career has come to an end
after exhaustion and hardship.
And here, I am completing my final
thesis with all my vigor and energy.
I dedicate my diploma and my joy
to my father, my mother,
and all the members of my family.
I must not forget my friends,
my teachers, and all those who have
supported and encouraged me in my life
and given me a helping hand.

Thank you.

BACHIR…

Dedication

My academic career has come to an end after exhaustion and hardship.
And here, I am completing my final thesis with all my vigor and energy.
I dedicate my diploma and my joy to my father, my mother, and all the members of my family.
I must not forget my friends, my teachers, and all those who have supported and encouraged me in my life and given me a helping hand.

Thank you.

SABER…

Thanks

First of all, we thank our supervisor

Dr. Mohammed Aroudj

For their valuable advice and assistance throughout the project. And to the members of the jury for their interest in our research by agreeing to review our work and enrich it with their suggestions. Finally, we would also like to thank everyone who was directly or indirectly involved in the completion of this work.

Summary

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List of abbreviations

L	Inductance [H]
C	Capacitance [F]
R	resistance [Ω]
I	current I [A]
V	Electric voltage
ZVS	Zero-Voltage-Switching
IGBT	Isolated Gate Bipolar Transistor
MOSFET	Metal Oxyde Semi-Conducteur
$\boldsymbol{E}$	induced voltage [V]
$\boldsymbol{\varphi}$	magnetic flux [Wb]
t	time [s]
λ	Thermal Conductivity
T	Temperature [K or °C]
P	Power [W]
$\boldsymbol{\mu}$	The absolute permeability
$\boldsymbol{\mu 0}$	Vacuum permeability ($\mu 0 = 4\,\pi\,10^{-7}$)
$\boldsymbol{\mu}$**r**	Relative magnetic permeability of the material under consideration [H/m].
$\boldsymbol{\sigma}$	Electrical conductivity of the metal [S/m].
$\boldsymbol{f}$	Frequency of the source used [Hz].
$\boldsymbol{\delta}$	Penetration Depth
$\eta_{\boldsymbol{e}}$	Electrical efficiency

$\boldsymbol{Pc}$	Power in the load.
$\boldsymbol{Pi}$	Power lost in the inductor turns.
$\vec{\boldsymbol{E}}$	Electrical excitation field [V/m]
$\vec{\boldsymbol{H}}$	Magnetic excitation field [A/m]
$\vec{\boldsymbol{D}}$	Electrical induction field [A.s/m]
$\vec{\boldsymbol{B}}$	Magnetic induction field [T]
$\vec{\boldsymbol{J}}$	Surface density of electric current [A/m^2]
$\boldsymbol{\rho}$	Volume density of electric charge [C/m^3]
$\boldsymbol{\varepsilon}$	Electrical permittivity. $[F/m]$
$\boldsymbol{\varepsilon_0}$	Electrical permittivity of vacuum $\varepsilon_0 = \frac{1}{\mu_0 C^2} = \frac{10^{-9}}{36\pi} F/m$
$\boldsymbol{\varepsilon_r}$	Relative electrical permittivity of the medium considered.
$\boldsymbol{C}$	Speed of light. $C = 3.10^8 m/s$
$\boldsymbol{\omega}$	The electrical angular frequency
$\boldsymbol{v}$	Denotes magnetic reluctance $\boldsymbol{v} = \frac{\mathbf{1}}{\boldsymbol{\mu}}$
$\boldsymbol{\chi}$	The magnetic susceptibility of the material
$\emptyset$	Phase shift between current and voltage

General introduction

General introduction

The Electromagnetic systems are systems often governed by the phenomenon of induction.

In 1820, Danish scientist Hans Christian Oersted observed that a current passing through a wire near a compass deflected the compass needle, leading to the discovery of the creation of a magnetic field from a direct current. At the same time, Englishman Michael Faraday questioned the possibility of creating a current from a magnetic field. In 1821, Faraday created the first electric motor. Ten years later, thanks to American work on copper coils, Faraday created the beginnings of the alternator, thus becoming the father of electromagnetism. Electromagnetic systems generally originate from a power electronics device, which is defined as the electronics component specialized in changing the shape of electrical voltages and currents, combining the energy aspect of electrical circuits. Also known as a static electrical energy converter, over time, these converters have evolved and developed technologically, and thanks to their use in electromagnetic systems, the latter have become both more complex and more efficient [1].

Electromagnetic devices always generate heating phenomena. This can be beneficial, as in the case of induction heating, or harmful, as in the case of electrical machines. The lifespan of these devices depends largely on the temperature reached in steady state. In induction heating, the goal is always to achieve higher or lower temperatures, localized and with high efficiency. An induction heating system consists of three main parts: the static power converter, which constitutes the power generator, the matching enclosure, and the inductor/load assembly.

In order to accomplish the goal of this work, we have distilled this issue into four essential chapters:

- Chapter I : Fundamentals of Electromagnetic Induction Heating
- Chapter II : Types and Applications of Induction Heating
- Chapter III : Design of the Installation of the Heating Induction
- Chapter IV : Results and Analysis

Chapter I :

Fundamentals of Electromagnetic Induction Heating

I.1. Introduction :

For various thermal processes, including melting or heating metals, electromagnetic induction is a common heating method for electrically conducting materials (metals). One special characteristic of electromagnetic induction is that it produces heat inside the substance that has to be heated. Compared to more conventional heating techniques, this characteristic has several benefits, such as shorter heating durations, higher efficiency [1]. No poisonous vapors or other fumes.

I.2. Induction heating's history :

The English physicist Michael Faraday made the discovery of magnetic induction in 1831. The 1900s saw the introduction of induction as a method of heating metal components, however its application was severely constrained by the little power available. Dynamic generators made it more efficient in 1922, and research on induction heating revealed that by adjusting the frequency, power, and material parameters like electrical resistivity and relative magnetic permeability, it was possible to heat some parts of a part without heating the others.

Later in the 1960s, the arrival of static generators with semiconductors allowed the use of higher power and frequencies. Today, induction heating is a well-mastered industrial process in a large number of fields, such as foundry, welding or hardening. [2].

I.3. Principle of induction heating :

Induction heating is a direct application of two physical laws: Lenz's law and the Joule effect.

Any electrically conductive material immersed in a variable magnetic field (created by an induction coil or inductor) is the site of induced electric currents or eddy currents. These currents dissipate heat through the Joule effect in the material where they originate. Indeed, a conductive medium, in this case an inductor, carrying a direct or alternating current, generates an electromagnetic field in the surrounding space.

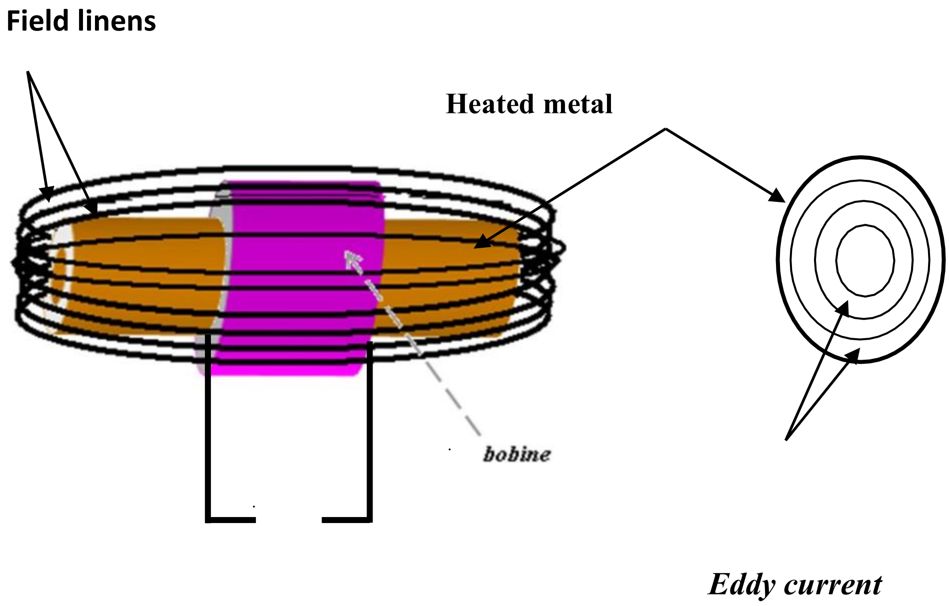


Figure 1.1: Principle of induction heating. [2].

Depending on the electromagnetic field's frequency and the characteristics of the material, the component can be penetrated from the surface to a larger or smaller depth.

Depending on whether the component is magnetic, non-magnetic, or diamagnetic, if an alternating current powers our inductor, the electromagnetic field will oscillate precisely or roughly at the same frequency as the imposed current.

Eddy currents are created in the component by these quick fluctuations of the electromagnetic field. The currents' movement and direction follow Lenz's law, which says that "induced currents oppose the cause that gave rise to them." As a result, the current imposed in the inductor will flow in the same direction as the current generated in the component, but in the opposite direction. The Joule effect causes the area that the currents pass through to dissipate heat. Lastly, thermal diffusion causes the heat to go toward the part's core. [3].

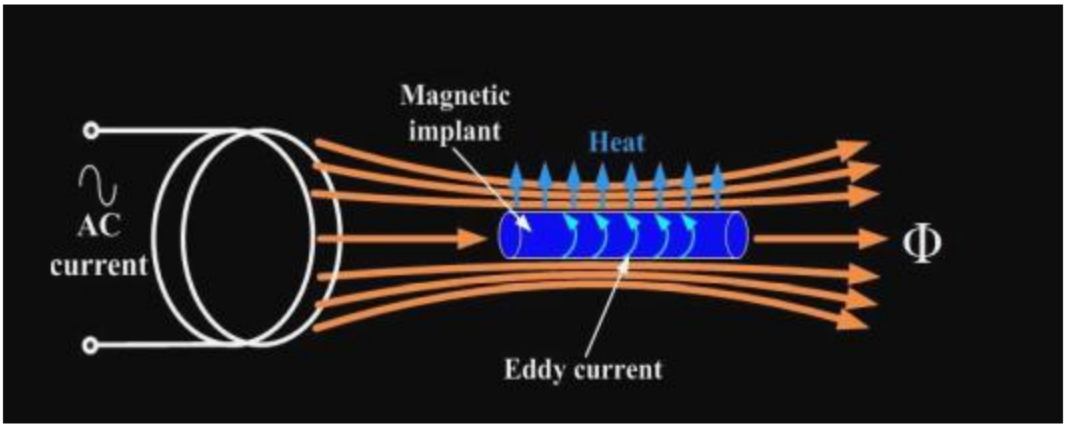


Figure 1.2: Principle of induction heatin. [3].

Three physical processes are involved in induction heating:

- ✓ Electromagnetic energy transfer from the inductor to the body to be heated.
- ✓ The Joule effect's conversion of electrical energy into heat within the part to be heated
- ✓ Heat transmission through thermal conduction in the mass. [4][5].

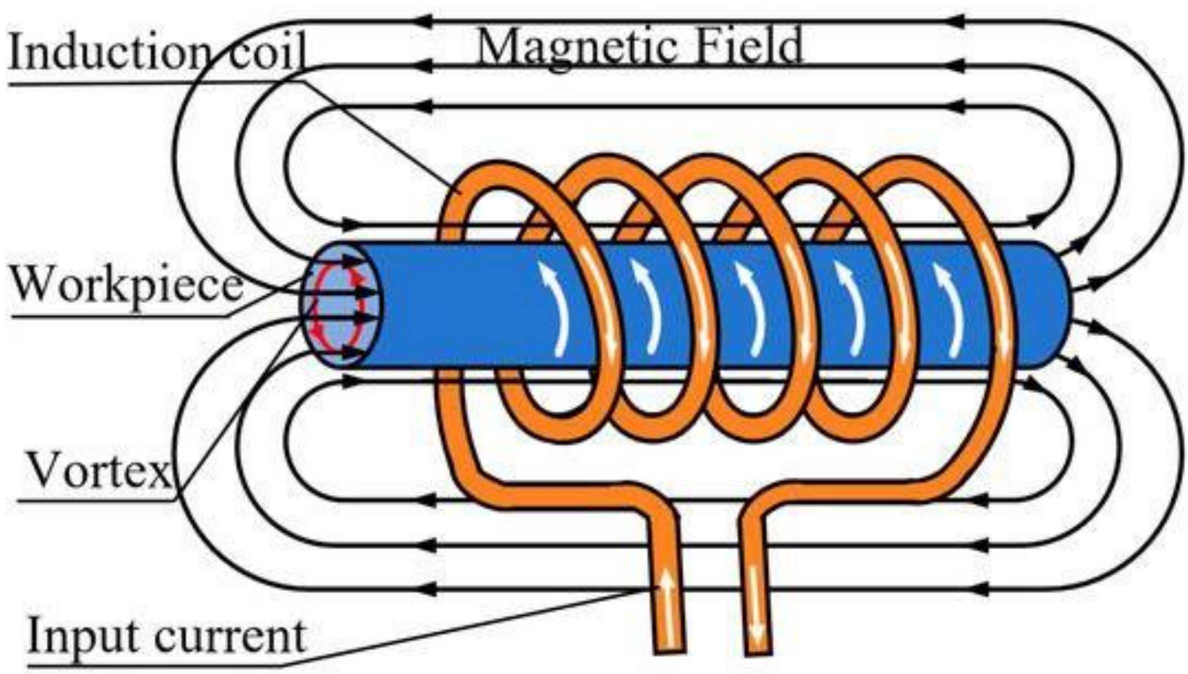


Figure I.3 : Principle of induction heating. [3].

I.4: Phenomena and physical laws related to induction heating:

I.4.1- Faraday and Lenz's laws:

An emf can be induced in a wire-like circuit by varying the magnetic flux through it: this is the phenomenon of electromagnetic induction.

Examples of variations in the magnetic field flux through a circuit include:

- ✓ The case of a moving circuit in a permanent magnetic field (Lorentz),
- ✓ The case of a fixed circuit in a variable magnetic field (Newman),
- ✓ The general case of a moving circuit in a variable magnetic field.

The direction of the induced current is determined by Lenz's law, which specifies that the induced current must be directed in a way that opposes the flux fluctuation that caused it. An electromotive field operating on the circuit's charge carriers is implied if the emf produces an electric current when the circuit is closed. The induced electric field is the name given to this field. [6].

Using Faraday's law, the induced emf E is stated as follows for a period and the fluctuation of the total magnetic flux across any surface lying on the circuit (C):

$$E = -\frac{d\varphi}{d\tau} \qquad \text{(I. 1)}$$

E: induced voltage [V]

Q: magnetic flux [Wb]

t: time [s]

The study of electromagnetism is based on this rule, which was discovered experimentally for relatively gradual fluctuations of the magnetic flux as a function of time. It is applicable to any variable regime. [1] [6].

Equation (I.1) states that an induced voltage E is produced at the loop's terminals when a conductive material loop (see figure I.2a) is exposed to a magnetic field.

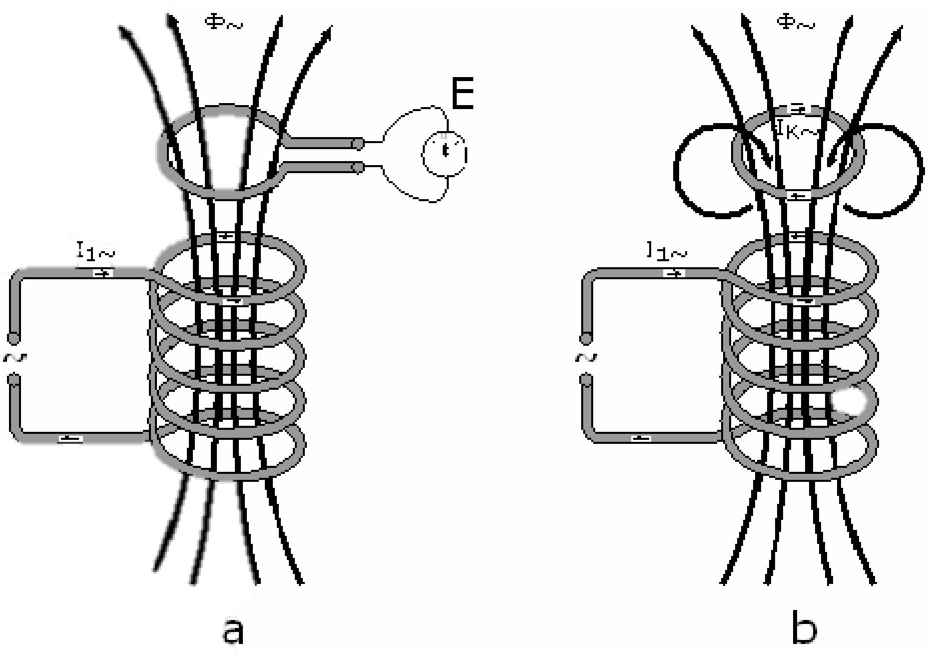


Figure I.4: Faraday's law. [1].

A short-circuit current flowing in the opposite direction of the phenomena that causes it will arise when the loop is short-circuited due to the electromotive force E.

This graphic (I.2b) represents the Faraday-Lenz law. [1].

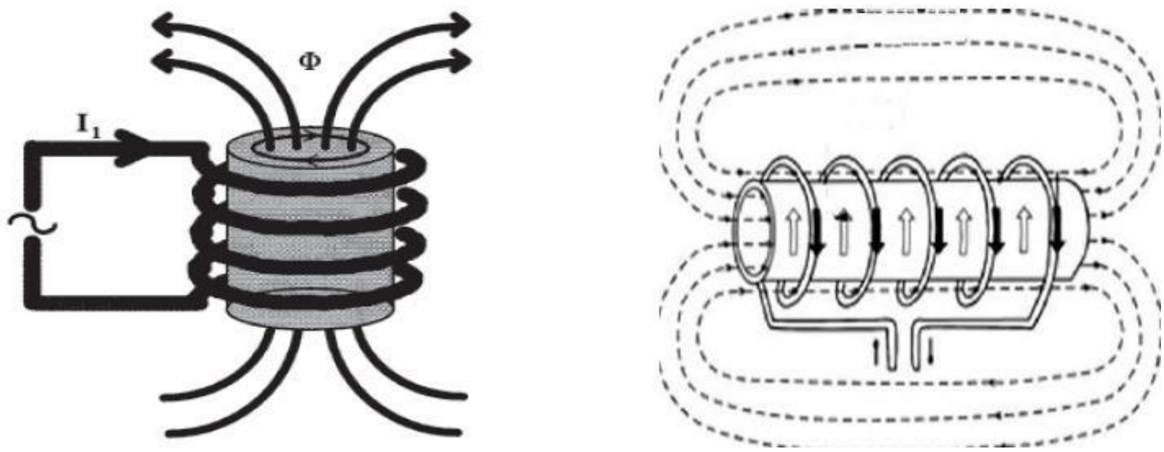
I.4.2- Joule effect :

The coil's alternating current will produce an alternating magnetic induction at the current's frequency if an alternating potential differential U is introduced to its terminals. A conductive object will experience a fluctuating magnetic flux if it is positioned close to the coil. According to Faraday's law, this flux will then create an electromotive force that will cause induced currents to flow through the conductor. The Joule effect causes these induced currents, also known as eddy currents, to heat the body [7].

When a current I [A] flows through an electrical conductor of resistance R [Ω], the dissipated power P [W] in the conductor is of the type:

$$P = R.I^2 \qquad \text{(I.2)}$$

Figure I.5: Joule effect. [1].



This action enables the induced currents to be converted into heat during induction heating, which is subsequently transferred into the body to be heated by thermal convection. [1].

I..4.3- Skin effect:

The distribution of induced currents in the area that has to be heated is described by the skin effect or penetration depth . A changing magnetic field applied to an electrically conductive material causes the density of induced currents to drop exponentially toward the part's center as it gets farther away from the surface. The term "skin effect" refers to these variations in the density of induced currentos, whose characteristic quantity is the skin thickness or the depth of magnetic field penetration. [8] [9].

The theoretical formula allows us to know the order of magnitude of the skin thickness [3]:

$$\delta = 1/\sqrt{(\mu 0 \, . \, \mu \mathrm{r} . f \pi \, \sigma)} \qquad \text{(I.3)}$$

$\mu 0$: Vacuum permeability ($\mu 0 = 4\,\pi\, 10^{-7}$)

μr : Relative magnetic permeability of the material under consideration [H/m].

σ : Electrical conductivity of the metal [S/m].

f: Frequency of the source used [Hz].

The penetration depth δ therefore depends on:

- ✓ The frequency of the variable field, and δ decreases as f increases,
- ✓ The nature of the material to be heated in terms of magnetic permeability and electrical conductivity.

The following table compiles δ orders of magnitude based on many :sources. Regarding various frequencies

Table I.1: Some values of penetration depth expressed in mm, for a relative permeabilityμrexcept steel at 20°C) 1=. [8] .

f(Hz)	**Steel** μr= 100 (20°C)	**Steel** (800°C)	**Cuivre** (20°C)	**Cuivre** (800°C)	**aluminium** (20°C)	**aluminium** (500°C)	**Graphite** (20-1300 °C)
50	3,18	67,2	9,35	19,4	11,9	19,4	201
100	2,25	47,5	6,61	13,4	8,4	13,4	142
10^3	0,71	14,6	2,09	4,26	2,66	4,26	45
10^4	0,225	4,75	0,661	1,34	0,84	1,34	14,2
10^5	0,071	1,46	0,209	0,426	0,266	0,426	4,5
10^6	0,0225	0,475	0,066	0,134	0,084	0,134	1,42
10^7	0,007	0,146	0,021	0,043	0,0266	0,043	0,45

I.4.4- Eddy Currents :

In addition, Foucault studied magnetic and electrical phenomena, including the electric currents that flow through a conductor as the magnetic field changes.

Thus, induced currents, also known as eddy currents, are produced when a time-varying magnetic field produces an electric field, which in turn causes the appearance of electric currents generated locally in the material.

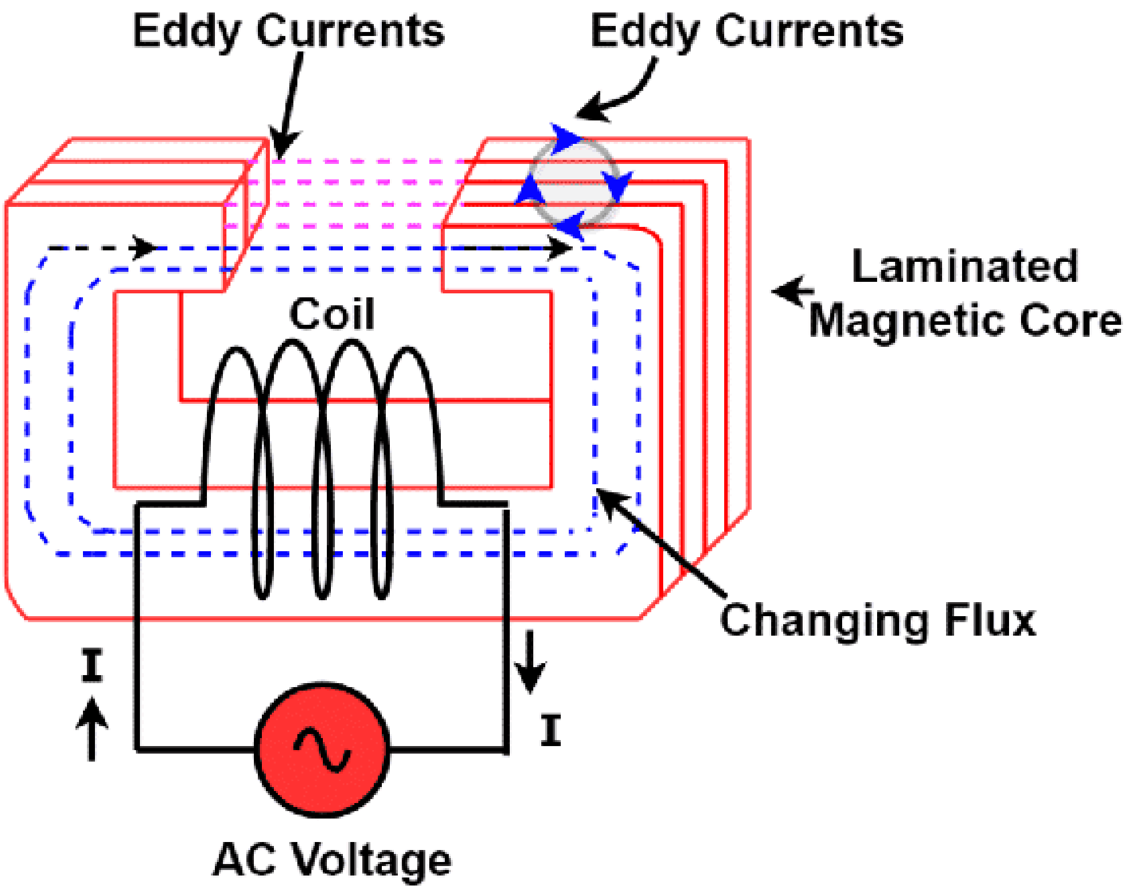


Figure I.6: Eddy Currents. [14].

Induction heating devices employ eddy currents to dampen or slow down the oscillations of a moving object since they flow in the opposite direction of inductive currents. However, they are dangerous in transformer cores and spinning electrical devices, where laminated conductors that block their propagation minimize their impact. [12,13].

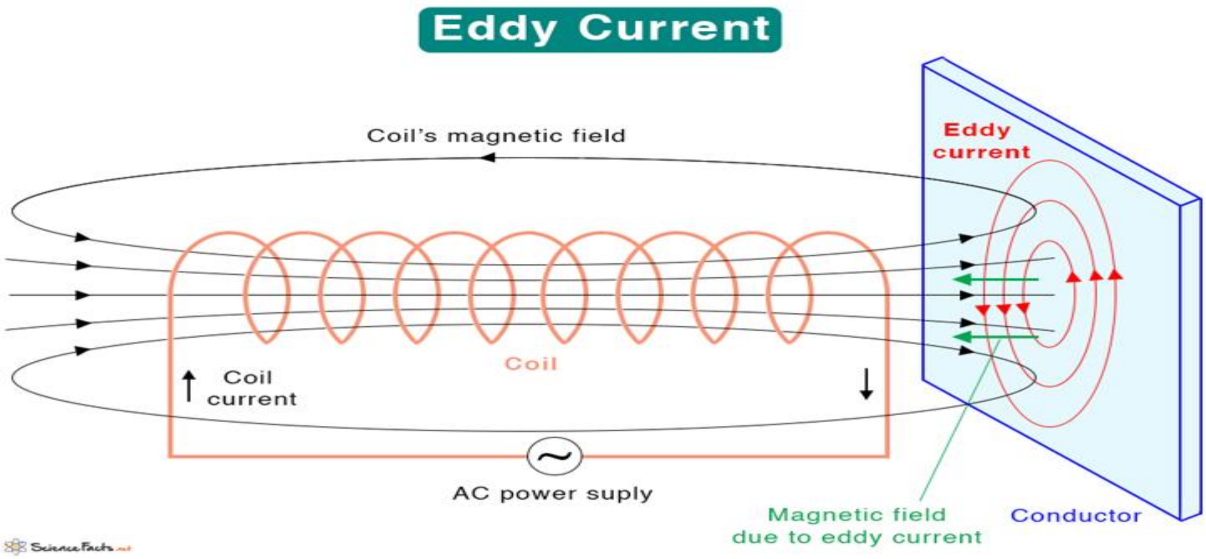


Figure I.7: Eddy Currents . [14].

I.5- Types of induction heating :

I.5.1- Direct heating :

Eddy currents develop directly in the part to be heated, causing it to heat up by the Joule effect.

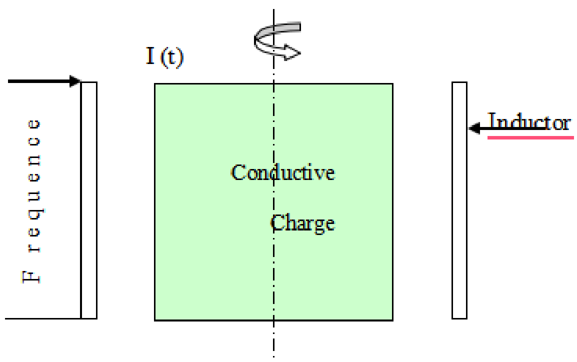


Figure 1.8: Direct induction heating. [14].

I.5.2- Indirect heating :

An element in thermal contact with the load induces currents.

The container may be coated or metallic when heated indirectly. In this instance, the heat spreads thermally into the portion to be heated, which is typically a non-conductive liquid, once the induced currents form in the container .

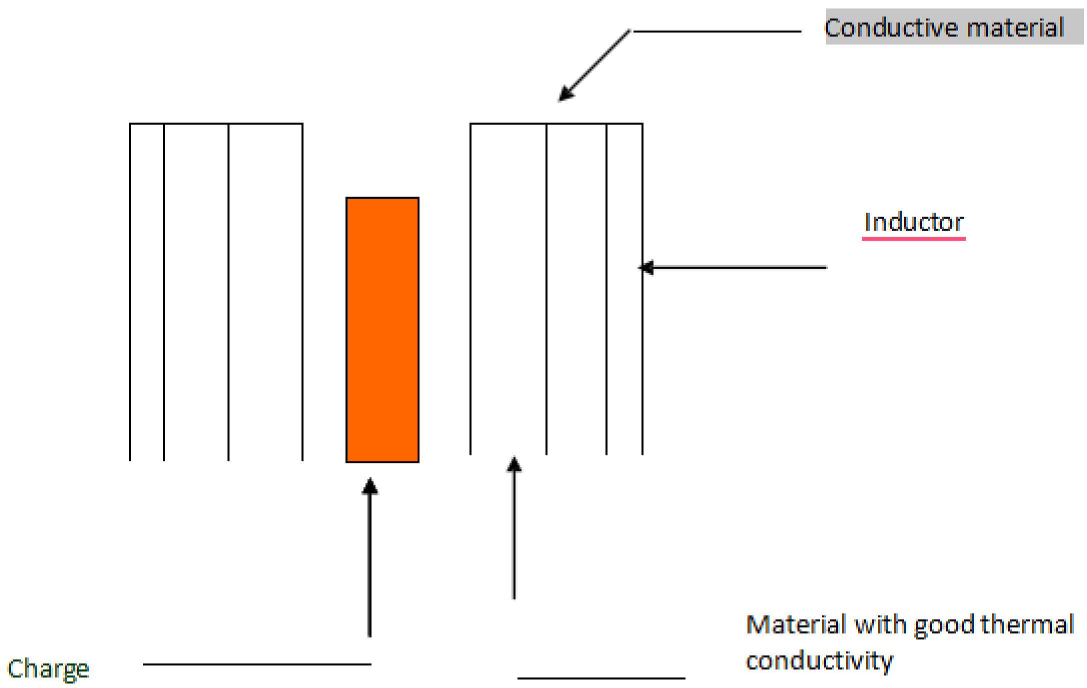


Figure 1.9: Indirect induction heating. [14].

The capacity to reach high working temperatures is one benefit of this kind of heating. [14].

I.6- Structure of an induction heating installation :

An induction heating device essentially comprises [15] :

- A power source, which typically consists of a converter to produce electrical currents at the necessary frequency and a medium or high-frequency generator,
- a bank of capacitors and a matching transformer needed for voltage regulation.,
- an inductor for heating.,
- a load that has to be heated.,
- a cooling mechanism for the inductor and additional parts of the power supply.,
- command and control devices.

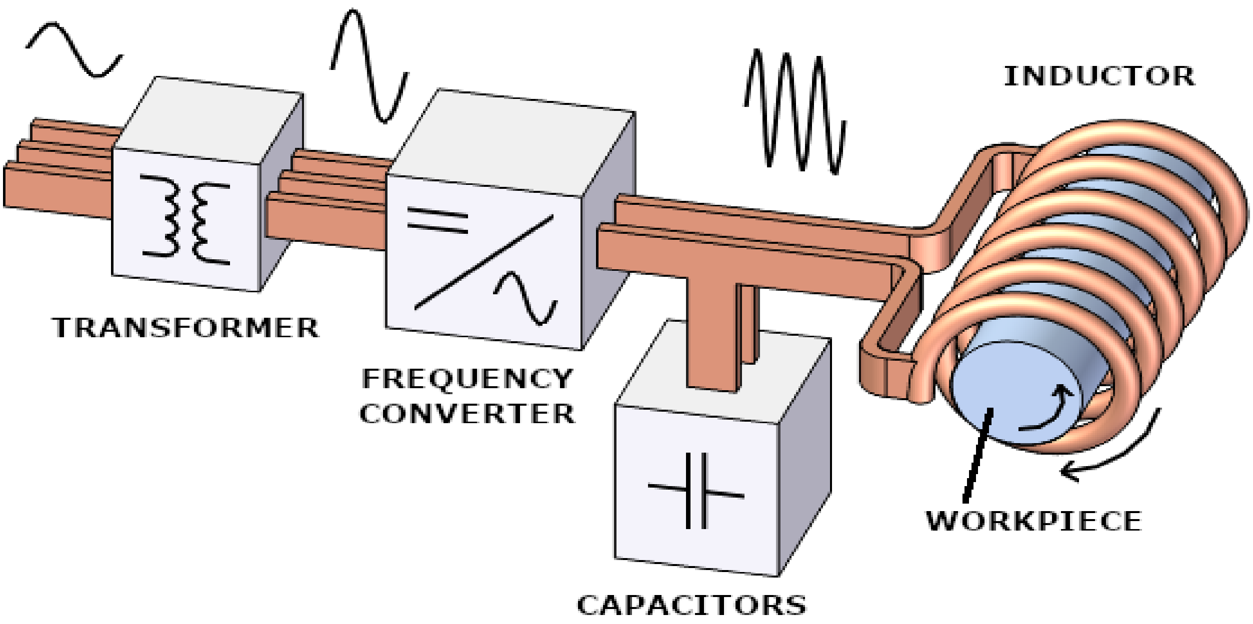


Figure I.10: Induction heating installation. [15].

I.6.1- Power supply and generator :

Depending on the installation's power supply frequency, the power supply may be of a different kind. [1].

A few orders of magnitude on induction heating allow us to better understand its specificities.

- For 50Hz installations

- The transformer is directly linked to the load. To adapt the currents to the load impedance, the transformer can be controlled. [1].

- Thyristor frequency converter:

- Efficiency: 90-97%
- Frequency range: 100Hz-10kHz
- Power range: up to 10MW

- Transistor frequency converter:

- Efficiency: 75-90%
- Frequency range: up to 500kHz
- Power range: up to 500kW

I.6.2- Inductor :

In the majority of uses, the inductor is a hollow copper tube that covers the item to be heated and resembles a winding. It is the one that generates the magnetic field. Depending on the application, the inductor might be positioned differently. [1].

In order to sustain large currents while producing the least amount of joule loss (limiting electrical losses), the inductor is often composed of copper and cooled by water. [1].

I.7- Properties of induction heating :

I.7-.1-Electrical efficiency :

The ratio of power delivered to the inductor's terminals to power dissipated in the load is known as electrical efficiency. [14].

$$\eta e = Pc/(Pi + Pc) \qquad (I.4)$$

With :

Pc: Power in the load.

Pi: Power lost in the inductor turns.

It strongly depends on the diameter/penetration depth ratio (in the case of cylindrical load) and the design of the inductor. The basic rules to follow for better efficiency are:

- High electrical resistivity magnetic metals perform better than low electrical resistivity metals.
- Ensure that the inductor and the load have a strong connection by limiting the air gap and making the inductor long enough.
- Reduce the space between the windings as much as possible. [14] [1].

I.7.2- Amplitudes of inducing currents :

The square of the magnetic field, or the square of the intensity generating the field, determines the transmitted power just as the frequency does. Thus, the strength of the inducing currents is selected based on the intended thermal use. [14].

I.7.3- Power :

The types of applications and frequencies utilized determine the powers required. They are distinguished by the particular power that is pumped into the space that has to be heated. Their range is between 100 KW/m^2 and 105 Kw/m^2. [17].

I.8- Conclusion :

We went over the basic idea of induction heating in this first chapter and gave a quick overview of its features. This technique's main advantage is that heat is produced directly in the substance that has to be heated. Response times are greatly shortened, and extremely high efficiency and customized heating capabilities are made possible.

It is evident that induction heating is growing quickly in the global industrial sector.

Chapter II :

Types and Applications of Induction Heating

II.1- Introduction :

Heat transport phenomena and electromagnetic phenomena interact intricately in the process of induction heating. We shall introduce the fundamental mathematical formulas in this chapter: The partial differential equations that explain such events are derived from Maxwell's equations for electromagnetism and the heat diffusion equations for thermal (electromagnetic, thermal &) .

II.2- Maxwell's equations :

The Maxwell-Lorentz equations, also referred to as Maxwell's equations, are essential physics rules. Together with the Lorentz force expression, they form the fundamental postulates of electromagnetism.

Prior to Maxwell combining them into integral equations, these equations translated into local form many theorems (Gauss, Ampère, Faraday) that regulated electromagnetic. As a result, they offer a rigorous mathematical foundation for the basic idea of field that Faraday introduced into physics in the 1830s. [20].

Specifically, these equations demonstrate that the electric and magnetic fields are independent of one another in a stable state, but not in a changing state.

Thus, we must refer to the electromagnetic field in the broadest sense. [20].

Maxwell - Ampère : $$\overrightarrow{rot}\,\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad \text{(II. 1)}$$

Maxwell - Faraday : $$\overrightarrow{rot}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \text{(II. 2)}$$

Maxwell - Thomson : $$div\,\vec{B} = 0 \qquad \text{(II. 3)}$$

Maxwell - Gauss : $$div\,\vec{D} = \rho \qquad \text{(II. 4)}$$

Where:

$\vec{E}$ [V/m]: electrical excitation field

$\vec{H}$ [A/m]: magnetic excitation field

$\vec{D}$ [A.s/m]: electrical induction field

$\vec{B}$ [T]: Magnetic induction field

$\vec{J}$ [A/m^2]: Surface density of electric current

ρ[C/m^3]: Volume density of electric charge.

II.3- Laws of behavior of environments:

Although Maxwell's equations provide the foundation of all electrical and magnetic phenomena, it is crucial to realize that they can never be solved in their current form since the relationship between matter and the electromagnetic field is yet unknown.

The behavioral relationships of the media (matters) where the electromagnetic field is dominant must be added to them in order to complete them. [21].

II.3.1- Ohm's Law:

$$\vec{J} = \sigma \vec{E} \qquad \text{(II. 5)}$$

$\sigma[(\Omega.m)^{-1}]$: Electrical Conductivity

II.3.2- Magnetic Relation:

$$\begin{cases} \vec{B} = \mu \vec{H} \\ \mu = \mu_0 \mu_r \end{cases} \qquad \text{(II. 6)}$$

II.3.3- Dielectric Relation:

$$\begin{cases} \vec{D} = \varepsilon\,\vec{E} \\ \varepsilon = \varepsilon_0\ \varepsilon_r \end{cases} \tag{II. 7}$$

$\varepsilon\ [F/m]$: Electrical permittivity.

$\varepsilon_0 = \frac{1}{\mu_0 C^2} = \frac{10^{-9}}{36\pi} F/m$: Electrical permittivity of vacuum.

ε_r : Relative electrical permittivity of the medium considered.

$C = 3.10^8 m/s$: Speed of light.

II.4- Simplifying hypotheses :

Displacement currents are negligible. Indeed, the electromagnetic structures we study are characterized by the same dielectric properties as those of a vacuum ($\varepsilon_{r=l}$). Furthermore, the operating frequency in induction heating operations is around twenty kHz. The displacement term in the case of sinusoidal excitation is:

$$\frac{\partial D}{\partial t} = \frac{\partial(\varepsilon_0 E)}{\partial t} = \frac{\varepsilon_0}{\sigma}\left[\frac{\partial j}{\partial T}\right] = J\,\frac{\varepsilon_0}{\sigma}\,\omega J \tag{II. 8}$$

With:

ω: The electrical angular frequency and $j^2 = -1$

The ratio R between the modulus of this current and the conduction modulus J for an electrical conductivity $\sigma = 34.10^6 (\Omega m)^{-1}$

Frequency f = 20 kHz

$\varepsilon_0 = 8.8\ 10^{-12}\ Fm$

$$R = \frac{\varepsilon_0}{\sigma}\omega = 3.2\ 10^{-14}$$

This allows us to neglect the effect of the displacement current.

- The volume charge density is assumed to be zero ($\rho = 0$).
- The supply currents are assumed to be generated by a perfect current generator;
- The remanent magnetic induction is assumed to be zero ($B_r = 0$) in the case where there is no permanent magnet;
- The surface current density between the two media is zero (K=0);
- We are interested in induction heating systems with very slow movements or no movement (v=0).

$$\sigma(v\Delta B) = 0 \qquad \text{(II. 9)}$$

$$J = J_s + \sigma E \qquad \text{(II. 10)}$$

With the assumptions thus formulated, the Maxwell equations to be solved are:

$$\begin{cases} rot(E) = -\frac{\partial B}{\partial t} \\ rot(H) = J \\ div(B)=0 \\ div(D)=0 \end{cases} \qquad \text{(II. 11)}$$

II.5- Solving Maxwell's equations:

Maxwell's equations constitute a first-order differential system which, in the general case, does not allow the E and B fields to be explained separately.

The use of the vector magnetic potential A and the electric scalar potential φ allows the number of unknowns to be condensed and reduced.

II.6- Formulation in terms of vector potential:

The magnetic vector potential A is defined by the following equation:

$$B = rot(A) \quad \text{(II. 12)}$$

In the general case, there exists an infinity of vector A that can satisfy the relation (II. 12). Indeed, since the rotational of the gradient of any scalar function f is zero, therefore any vector (A + grad(f)) satisfies the relation (II. 12), hence the need to impose a gauge condition in order to ensure the uniqueness of the solution. We propose to use the Coulomb gauge div(A) =0.

The equation we are about to establish applies to electromagnetic devices in which there are induced currents from fields over time.

Replacing B with rot(A), we obtain:

$$rot\left\{E + \frac{\partial A}{\partial t}\right\} \quad \text{(II. 13)}$$

From this relationship, we can define an electric scalar potential φ such that:

$$E + \frac{\partial A}{\partial t} = -grad(\varphi) \quad \text{(II. 14)}$$

Combining the equations gives (II. 10) and (II. 14) gives:

$$\sigma E = J - j_s = -\sigma\left\{\frac{\partial A}{\partial t} + grad(\varphi)\right\} \quad \text{(II. 15)}$$

From where

$$J = -\sigma\left\{\frac{\partial A}{\partial t} + grad(\varphi)\right\} + j_s \quad \text{(II. 16)}$$

By replacing J by its expression (II. 16) in equation (II. 11) we arrive at the condensed vector expression of the system of equations (II. 11) thus representing the electromagnetic equation in magnetic vector potential A, given by the following system of equations:

$$\begin{cases} rot\big(v\, rot(A)\big) = -\sigma \left\{ \frac{\partial A}{\partial t} + grad(\varphi) \right\} + j_s \\ div(A) = 0 \end{cases} \quad \text{(II. 17)}$$

Where $v = \frac{1}{\mu}$ denotes magnetic reluctance

Equation (II. 17) takes different forms depending on the region of study and the characteristics of the different environments.

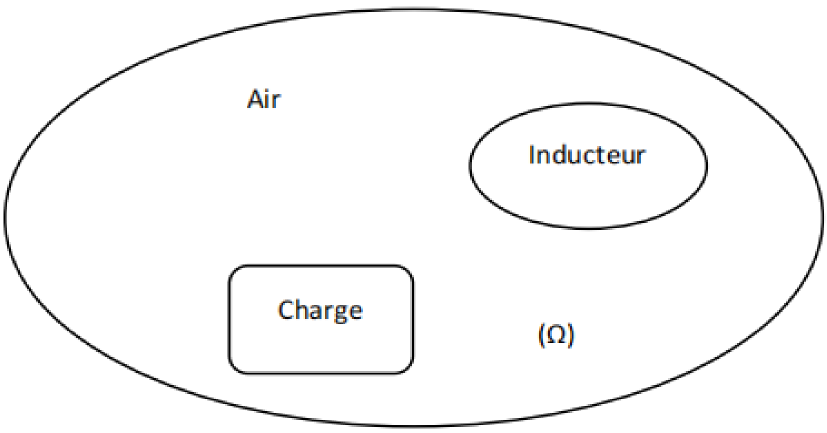


Figure II.1 : Typical electromagnetic problem.

Inductor region:

We consider two cases:

- □ The inductor is powered by a voltage source. In this case, the scalar potential φ is none other than the known voltage of the source V:

$$rot\big(v\,rot(A)\big) = -\sigma\frac{\partial A}{\partial t} - \sigma\,grad(V) \qquad \text{(II. 18)}$$

- The inductor is powered by a current source of density J_s and known amplitude,

whose distribution is uniform across the conductor cross-section. Equation (II. 16)

$$rot\big(v\,rot(A)\big) = J_s \qquad \text{(II. 19)}$$

Non-conducting region:

In our case, this region is made up of air. We then find the Laplace equation:

$$rot\big(\,rot(A)\big) = 0 \qquad \text{(II. 20)}$$

Conducting region:

The equation governing this region is:

$$rot\big(v\,rot(A)\big) = -\sigma\frac{\partial A}{\partial t} \qquad \text{(II. 21)}$$

With :

$-\sigma\,grad(V) = 0$

II.7- Coupled electromagnetic equations:

The electromagnetic phenomena is reduced to an induction phenomenon by the earlier approximations.

With a suitable selection of the state variable, the phenomena is examined in accordance with the device geometry. Since our configuration is spiral (cylindrical), it is preferable to use the magnetic vector potential or the electric field as the state variable since they only contain a component that is orthogonal to the study plane.

This component is in the angular direction and alone depends on r and z in the case of axisymmetric systems represented in cylindrical coordinates.

The components of the different vector quantities in our scenario are as follows:

$$\vec{J}=\begin{cases}0\ \overrightarrow{e_r}\\ J_\varphi\ \overrightarrow{e_\varphi}\\ 0\ \overrightarrow{e_z}\end{cases}\quad \vec{E}=\begin{cases}0\ \overrightarrow{e_r}\\ E_\varphi\ \overrightarrow{e_\varphi}\\ 0\ \overrightarrow{e_z}\end{cases}\quad \vec{A}=\begin{cases}0\ \overrightarrow{e_r}\\ A_\varphi\ \overrightarrow{e_\varphi}\\ 0\ \overrightarrow{e_z}\end{cases}\quad \vec{B}=\begin{cases}B_r\ \overrightarrow{e_r}\\ 0\ \ \overrightarrow{e_\varphi}\\ B_z\ \overrightarrow{e_z}\end{cases}\quad \vec{H}=\begin{cases}H_r\ \overrightarrow{e_r}\\ 0\ \ \overrightarrow{e_\varphi}\\ H_z\ \overrightarrow{e_z}\end{cases}$$

(II. 22)

Since vector A is confused with its ortho-radial component, its divergence is therefore automatically zero. Under these conditions, the system of equations is reduced to:

$$rot\big(v\,rot(A)\big)=-\sigma\frac{\partial A}{\partial t}-\sigma\,grad(\varphi)+J_s \qquad \text{(II. 23)}$$

However, in an axisymmetric configuration, the term grad(φ) is zero. Thus, equation (II. 23)

takes the following form:

$$rot\big(v\,rot(A)\big)+\sigma\frac{\partial A}{\partial t}=J_s \qquad \text{(II. 24)}$$

Being aware that we have the following in a cylindrical coordinate system:

$$\overrightarrow{rot}\ \vec{A} = \begin{cases} -\frac{\partial A_\varphi}{\partial t} & \overrightarrow{e_r} \\ 0 & \overrightarrow{e_\varphi} \\ \frac{1}{r}\frac{\partial(rA_\varphi)}{\partial t} & \overrightarrow{e_z} \end{cases} \qquad \text{(II. 25)}$$

This reduces the vector form (II. 24) to the following relation:

$$\overrightarrow{rot}\ \vec{A} = \frac{1}{r}\left(-\frac{\partial(rA_\varphi)}{\partial z}\right)\overrightarrow{e_r} + \left(\frac{1}{r}.0\right)\ \overrightarrow{e_\varphi} + \frac{1}{r}\left(-\frac{\partial(rA_\varphi)}{\partial r}\right)\overrightarrow{e_z}$$

(II. 26)

$$\overrightarrow{rot}\ \vec{A} = \frac{1}{r}\left(-\frac{\partial(rA_\varphi)}{\partial z}\right)\overrightarrow{e_r} + \frac{1}{r}\left(-\frac{\partial(rA_\varphi)}{\partial r}\right)\overrightarrow{e_z}$$

(II. 27)

And : $\overrightarrow{rot}\left(v\,\overrightarrow{rot}\ \vec{A}\right) = \left[-\frac{\partial}{\partial r}\left(\frac{v}{r}\frac{\partial(rA_\varphi)}{\partial r} - \frac{\partial}{\partial z}\left(v\frac{\partial A_\varphi}{\partial z}\right)\right)\right]\overrightarrow{e_\varphi}$

(II. 28)

In which we set $A = rA_\varphi$, becomes:

$$\frac{\partial}{\partial z}\left(\frac{v}{r}\frac{\partial A}{\partial z}\right) + \frac{\partial}{\partial z}\left(\frac{v}{r}\frac{\partial A}{\partial z}\right) - \frac{\partial}{\partial z}\left(\frac{v}{r}\frac{\partial A}{\partial z}\right) \qquad \text{(II. 29)}$$

II.8- Thermal Phenomena

II.8.1- Heat Transfer Modes:

Convection, radiation, and thermal conduction are the three ways that heat is transferred.

The most common method of heat transmission in indirect heating via electrical conduction or electromagnetic induction is thermal conduction.

II.8.1.1- Conduction and thermal conductivity :

The transfer of heat from the hotter to the cooler areas of the same body or two in touch without any discernible movement of substance or movement involving thermal energy is known as thermal conduction.

Heat transmission between solids or between neighboring solids is the main use for thermal conduction. Conduction transfers in liquids and gases are often negligible in comparison to convectional transfers.

Thermal conduction is the process by which all heat exchanges between two bodies at differing temperatures take place across a wall. For instance, heat transfers in heat exchangers demonstrate this. [22].

II.8.1.2- Convection:

A certain amount of energy may be transported by a liquid or gas circulation or flow, and this flow is comparable to the movement of other scalar (non-vector) quantities. Thus, we'll keep in mind that heat moves through a fluid by convection. Without getting into specifics, let's say that convective transfers come in two varieties: [23].

- Forced convection,
- Natural convection.

In convection, the heat flux $\emptyset$ extracted by the fluid of temperature T_0 from a wall of surface S at temperature T_p is characterized by :

$$\emptyset = \mathrm{h}S(T_p - T_0) \qquad \text{(II. 30)}$$

II.8.1.3- Radiation :

Heat transfer by thermal radiation is accomplished by electromagnetic vibrations that travel without the use of material support.

The term "radiation" refers to the emission or absorption of electromagnetic radiation. [24].

II.8.2-The Heat Equation

II.8.2.1- Fourier's Law :

The only way heat can move through an opaque substance is by thermal conduction. [24].

With the notion of figure (II. 1), Fourier's law expresses that the heat flux density vector φis proportional to the temperature gradient T and is oriented in the opposite direction.

$$\vec{\varphi} = -\lambda \ \overrightarrow{grad}\, T \qquad \text{(II. 31)}$$

The coefficient λ called thermal conductivity of the medium, or more rarely thermal conductivity. It is expressed as $\mathrm{W.m^{-1}.K^{-1}}$.[22].

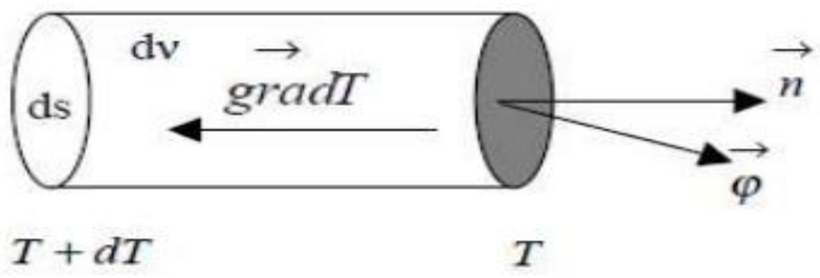


Figure II.2: Fourier elementary volume.[22].

II.9- Electromagnetic-thermal coupling :

Calculation of the coupling parameter between the two electromagnetic and thermal phenomena: represented by the power induced by the Joule effect in the load to be heated. This power ensures the physical coupling.

Knowing the distribution of potential A, we can deduce that of the induced current densities, the power jet P.

$$J = j\omega\sigma A \qquad \text{(II. 44)}$$

$$p = \frac{1}{2}\sigma\omega^2 A.A^* \qquad \text{(II. 45)}$$

With:

A^* : Is the complex conjugate of A

II.10. Geometries and types of inductors :

Since each induction heating application requires a different heating profile, induction heaters may be found in a broad range of shapes and sizes..

The kind of generator being utilized and the necessary heating profiles both influence the inductor shape [9].

Copper tubes that have been cooled by water are used as conductors in induction coils.

There are several types of inductors [10], including:

A. Multi-turn Helical Coil :

Figure II.3 Multi-turn Helical Coil. [10].

The helical (solenoid) coil is a very commonly used coil containing several turns defining the width of the heating model. In order to render a specific heating band during single shot heating, the work piece can be kept stationary in the coil or, a highly consistent heating pattern termed as scan heating can be used wherein the work piece is pushed through the coil.

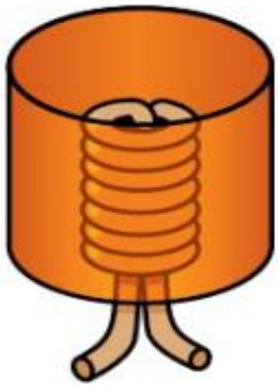


Figure II.4.Internal inductor : [10].

B. Single-Turn Coil :

Single-turn coils are perfect for heating either a narrow portion of a work piece or the work piece tip. It is also possible to use these coils to scan the work piece along its length and is usually used for heat treating. These coils are mostly tightly fixed to the part to provide an accurate heat pattern.

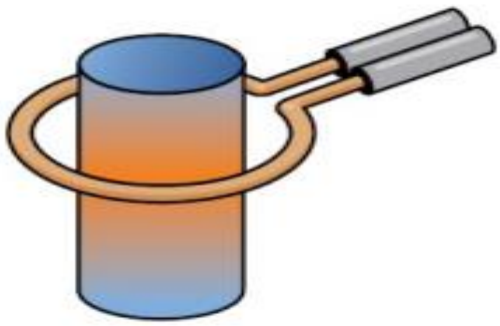


Figure II.5.Single-turn inductor : [10].

C. Multi-position helical inductor :

Multi-position coils are frequently used to generate more parts within a specific time while permitting the complete heating process. When a single work piece is heated at one position, another coil can be unloaded and reloaded for the subsequent heating cycle. Numerous positions are possible; however up to eight positions are realistic.

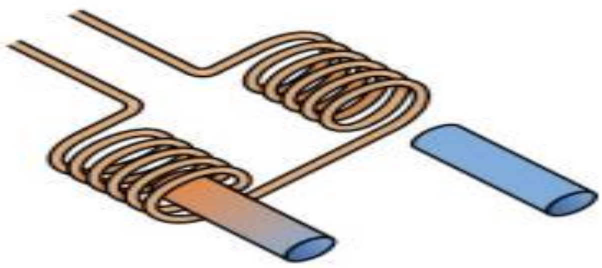


Figure II.6.Multi-position helical inductor : [10].

D. Channel Coil :

A coil can be designed in such a manner that the work piece moves via the electromagnetic field by linear transport mechanism. The work piece gets heated as it passes via the channel coil, and the coil can be constructed to heat all of the parts or only a single band.

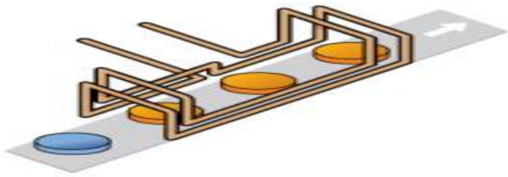


Figure II.7: Tunnel Inductor. [10].

E. Curved channel inductor :

Channel coils are mostly curved to fit onto a rotary table. They are designed to occupy one of the stages in a multi-step assembly procedure.

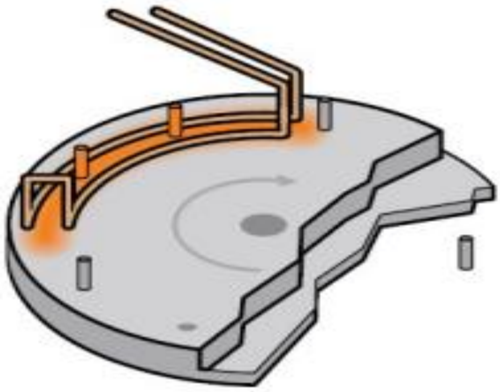


Figure II.8.Curved channel inductor : [10].

F. Pancake Coil :

Pancake coils are used in case the work piece has to be heated from just one side or when it is not possible to surround the entire component.

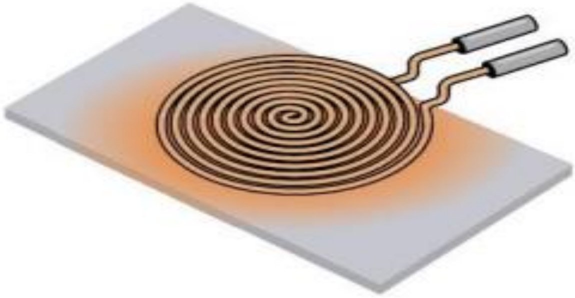


Figure II.9 Pancakes Inductor :. [10].

G. Split Helical Coil

In cases where it is not possible to obtain access to the heated area using a helical coil, a single or multiple turn split helical coils are used.

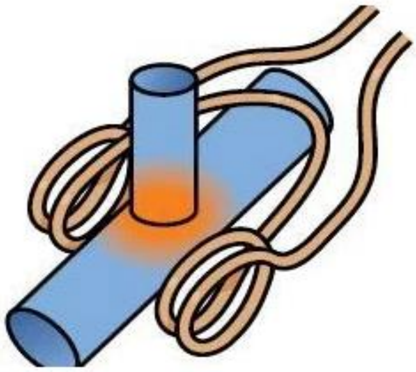


Figure II.10.Shared helical inductor : [10].

H. :Special shape

a. :Concentrating plate inductor

Concentrator plates are used in single-turn and multi-turn inductors to produce a defined heating effect within the workpiece. These inductors can also have a main inductor, equipped with inserts designed to heat workpieces of .various shapes

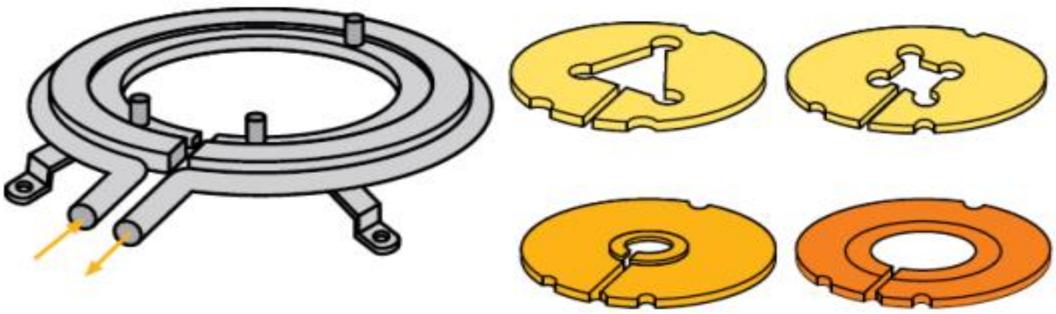


Figure II.11.Concentration plate inductor : [10].

b. :Reels and conveyors

Many parts are heated during transport on a conveyor system.

As long as the conveyor material is not electrically conductive, the magnetic field passes through it, heating the part as it passes through.

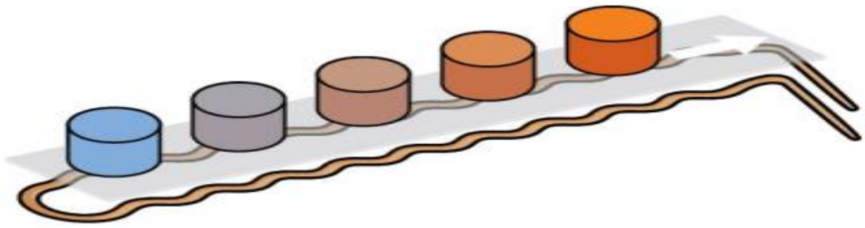


Figure II.12: Coils and conveyors. [10].

c. :**Hairpin Inductor**

It is a long, thin inductor with one or more turns used to heat a long, narrow area on a workpiece or to heat a moving strip of thin steel or aluminum.

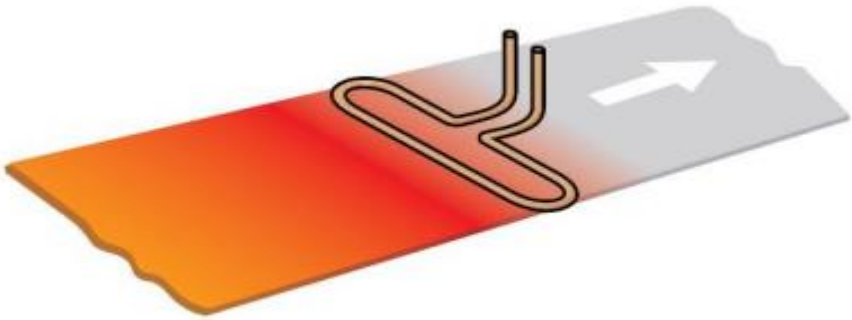


Figure II.13.Hairpin inductor : [10].

II.11. Body to be heated :

An electrically conductive substance must be used to heat the body. The material's thermal, electrical, and magnetic characteristics are among the variables that affect this heating **[11]**.

II.11.1. Magnetic Properties :

In a vacuum, the magnetic induction field vectors $\vec{B}$ and the magnetic excitation field vectors $\vec{H}$ are collinear and related by the following equation:

$$\vec{B} = \mu_0 . \vec{H} \quad \text{(II.46)}$$

μ_0: the magnetic permeability of a vacuum (T.m/A).

We define the magnetization vector $\vec{J}$, which indicates the influence of the medium. The excitation field and magnetization are superimposed to express the induction field:

$$\vec{B} = \mu_0 . \vec{H} + \mu_0 . \vec{J} \quad \text{(II.47)}$$

Now, the magnetization is proportional to the excitation field, so that:

$$\vec{J} = \chi.\vec{H} \qquad \text{(II.48)}$$

χ : is the magnetic susceptibility of the material

This results in a new expression linking $\vec{B}$ and $\vec{H}$:

$$\vec{B} = \mu 0.\mu r.\vec{H} = \mu 0\,(1+\chi)\,\vec{H} = \mu.\vec{H} \qquad \text{(II.49)}$$

μr: the relative permeability of the material.

μ: the absolute permeability

Materials can be classified according to their magnetic behavior, i.e., according to their magnetic susceptibility and their relative permeability as follows [3]:

a) Diamagnetic:

The susceptibility χ is low (therefore $\mu \approx 1$). Weakly magnetic material. If a bar magnet is placed near it, it repels it.

Examples: bismuth (Bi), silver (Ag), lead (Pb), water.

b) Paramagnetic:

The susceptibility χ is low (therefore $\mu \approx 1$). Exhibits very little magnetism. Attracted by a bar magnet.

Examples: air, aluminum (Al), palladium (Pd), molecular magnet.

c) **Ferromagnetic:**

The susceptibility χ is high ($\mu >> 1$). Magnetic par excellence or strongly magnetic. Attracted by a bar magnet.

Examples: iron (Fe), cobalt (Co), nickel (Ni), mild steel.

d) **Antiferromagnetic:**

Non-magnetic, even under the action of an induced magnetic field. Example: manganese oxide ($MnO2$).

Curie Temperature:

In a ferromagnetic or ferrimagnetic material, the Curie temperature, or Curie point, is the temperature (TC) at which the material loses its spontaneous magnetization. Above this temperature, the material is in a disordered state known as paramagnetic. This phase transition is reversible; the material regains its ferromagnetic properties when its temperature drops below the Curie temperature.

In induction heating, the magnetic properties of the body influence the power density transferred to the material and the power concentration zone. This zone becomes increasingly narrower for higher μr values. It is therefore easier to heat steel below its Curie temperature ($\mu r > 1$) than above it ($\mu r = 1$), which is why ferromagnetic materials are the most suitable for this heating system. Moreover, most cookware designed for induction cooktops is made of steel.

II.11.2.2. Electrical Properties: :

Among all materials, three categories can be distinguished:

1. Materials that conduct electricity: conductors
2. Materials that do not conduct electricity: insulators.
3. Materials that allow more or less electric current to pass through, which are called semiconductors.

The ability of a material to oppose the flow of electric current is called resistivity (the inverse of conductivity): it corresponds to the resistance of a section of material 1 m long and 1 m² in cross-section.

Its unit is the ohm-meter [Ω.m], its symbol is ρ.

Resistivity varies with temperature. For a very pure metal, resistivity can vary by a factor of 10^5 from a temperature close to 0°K to room temperature: 20°C. In induction heating, the electrical resistivity of the body to be heated plays a decisive role in the power received.

At a frequency of 10 kHz, an aluminum part heats more than a copper part of the same dimensions.

II.11.2.3. Properties of Heat:

The physical property that describes a body's capacity to transfer heat is called thermal conductivity. It is represented by the Greek letter λ, which means lambda. The heat transport mechanism linked to this amount is thermal conduction.

A substance is less insulating the greater its thermal conductivity, which indicates how much heat it conducts [12].

The thermal behavior of the body to be heated is described by thermal conductivity (λ), density, and specific heat (specific heat) in induction heating [13].

II.12. Penetration depth:

The depth at which 63% of the induced current density, or 86% of the transmitted power, is concentrated is known as the penetration depth, δ, or skin thickness. The following is an expression for the penetration depth:

$$\delta = \sqrt{\frac{\rho}{\pi \,.\mu 0 \,.\mu r \,.f}} \qquad \text{(II.50)}$$

With,

- ρ: Resistivity [Ω.m],
- μ0: No-load magnetic permeability () [H/m],
- μr: Relative magnetic permeability,
- f: Frequency [Hz],
- J0: Current density at the armature surface (x = 0);

Both the frequency of the current passing through the body to be heated and its electromagnetic characteristics affect this magnitude. It is smaller at higher frequencies, meaning that the induced currents are closer to the material's

surface at higher frequencies **[8]**. Thus, frequency serves as a lever to regulate penetration depth and aids in identifying the appropriate applications.

The penetration depth is determined by the material's electromagnetic characteristics, which include resistivity and magnetic permeability.

These characteristics are influenced by temperature. The magnetic permeability coefficient (μr) is greater for ferromagnetic materials (such iron and many types of steel) than for non-magnetic materials (like copper or aluminum), which have μr = 1. Therefore, the penetration depths of these later materials are significantly smaller.

As a result, the coefficient is highly dependent on the material's characteristics and the applied circumstances. It is well known that the permeability rapidly decreases to μr =1 above the Curie temperature, leading to a significant rise in the penetration depth. **[2]**

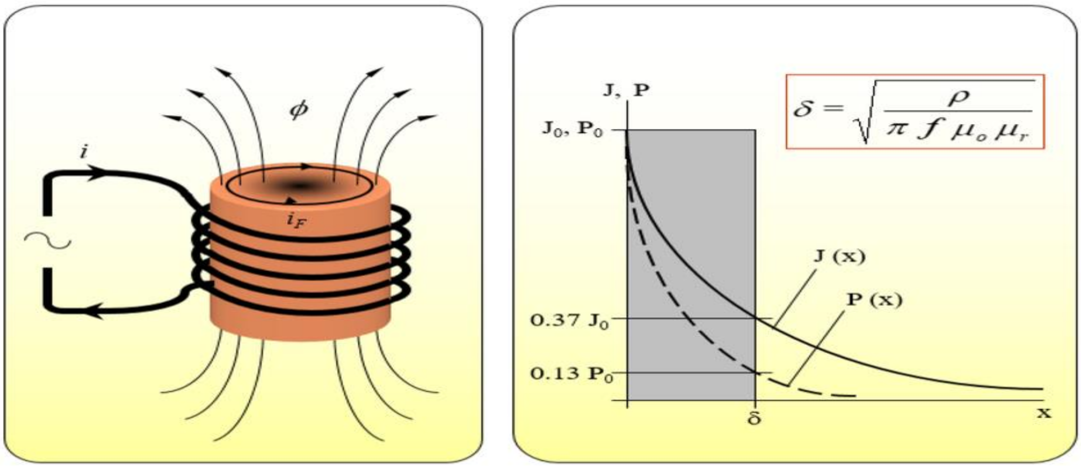


Figure II.14: Representation of penetration depth. [2]

II.13. Characteristics of the induction power generator:

II.13.1. Generator power:

The simple formulation of power RI² cannot be used due to the non-uniformity of the distribution of induced currents in the body to be heated **[15,16]**.

The absorbed power can be described by:

$$P = \rho . J^2 \qquad \text{(II.51)}$$

J = being the induced current density.

II.13.2. Efficiency:

Electrical efficiency is defined as follows:

- P: Power transmitted to the load
- Pi: Power dissipated in the inductor

Efficiency depends heavily on the diameter/penetration depth ratio (in the case of a cylindrical load) and the inductor design. The basic rules to follow for better efficiency are **[16]**:

i. For the inductor, use a low-resistance material, generally electrolytic copper.

ii. Minimize the distance between the windings.

iii. Establish a good connection between the inductor and the load (limit the air gap, and make the inductor sufficiently long).

II.13.3. Power factor:

An inductive load that uses reactive energy is comparable to the inductor and load assembly. The air gap (between the inductor and the load) and the load's own inductive behavior (in the case of a cylinder) are the two main causes of this inductive nature.

II.14. Induction heating applications:

Metallurgy and mechanics are the primary industries that use induction heating systems: 45% for melting, 45% for heating prior to forming, and 10% for heat treatment and other uses.

Large melting systems may require several megawatts of electricity, whereas tiny laboratory or dentistry induction furnaces may only require a few hundred watts **[17]**.

However, new uses have surfaced in other domains, such as chemistry (direct melting of glasses and oxides, etc.) and consumer electronics (kitchen induction hobs), as a result of advancements in power electronics technology and the development of quicker switching components.

II.14.1- Fusion:

The most often used furnaces are channel furnaces, which are frequently used to regulate the temperature of molten metals, and tilting crucible furnaces, which are primarily used for melting.

II.14.1.1 Crucible induction furnaces:

It basically consists of an inductor coil that is cooled by water circulation encircling a rammed earth refractory lining, creating a crucible that contains the metallic mass that has to be melted. The magnetic leakage flow is channeled by magnetic yokes.

Due to the substantial mechanical forces exerted by electromagnetic forces and rammed earth push (expansion, metallostatic thrust), the coil is kept firmly in place. These furnaces can have capacity of many tens of tons and range in power from a few kW (for melting precious metals) to around 10 MW. [17].

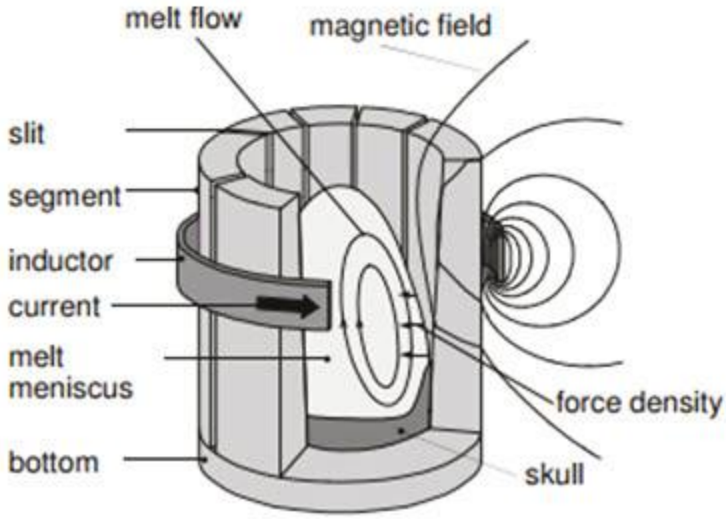


Figure II.15: Schematic diagram of a crucible melting furnace. [7]

II.14.1.2 Crucible induction furnaces:

In a channel furnace, a channel with two ends that enter into the tank is connected to the tank. The communication channel encircles the induction coil. The channel furnace is comparable to a transformer with a closed magnetic circuit, of which the channel would be the secondary, from an electrical perspective. [7]

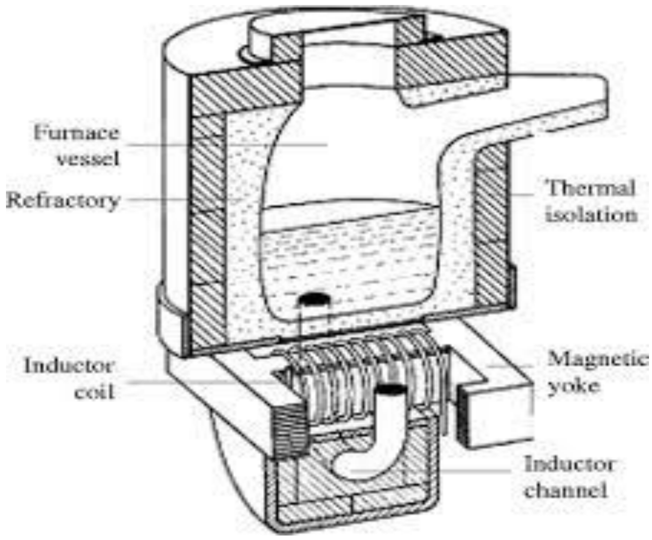


Figure II.16: Channel furnace. [7].

Under the influence of induced currents, the Joule effect causes the metal in the channel to heat up. Both the electromagnetic and thermosiphon effects are responsible for the metal's movement through the channel. A minor mixing is produced by the metal migrating between the crucible and the channel; this mixing is far weaker than in crucible furnaces. The channel furnace requires the inductors to be powered once the furnace has been filled with liquid metal. [7]

Because of the furnaces' consistent temperature and gentle stirring, these furnaces enable the creation of high-quality metal and alloys with good homogeneity.

II.14.2- Heating before formatting of metals:

A metal's plastic deformation is greatly aided by heating it within the bulk. The temperature is evenly raised to around 1100–1300°C for steels, 750–900°C for copper alloys, and 450–550°C for aluminum alloys for parts with a typically simple shape. [17]

Core heating requires a relatively low frequency, but the efficiency expression establishes a minimal threshold beyond which energy efficiency falls. Conversely, an extremely high frequency would cause too surface heating, extending the core heating time and raising all thermal losses. [17]

Two types of reheating are known:

- reheating before rolling,
- reheating before forging.

II.14.3- Induction heat treatment:

We may differentiate between mass treatment, for which induction is only starting to gain traction, and surface heat treatment or quenching, which is the most well-known use of induction heating. The commercialization of transistor frequency generators, which are now replacing traditional tube generators due to their higher efficiency (85-90% as opposed to 65-70%), is helping these applications, which frequently call for the use of high frequencies for induction (usually 50 to 400 KHz). [17]

- surface hardening,
- heat treatments in the mass,
- surface treatments.

Induction heating has a wide range of uses in both residential and commercial settings [18]. These consist of:

- Melting of metals or their alloys,

- Welding of metal parts,

- Shrink fitting,
- Reheating before forming and forging,
- Chemical industry,
- Inductive plasma,
- Hobs.

A. Melting metals or their alloys:

frequently used to keep molten metals at a consistent temperature, tilting furnaces, which are primarily used for melting, and crucible furnaces.

Crucible furnaces are made up of a coil that is cooled by water circulation and encircles a refractory lining that is filled with the material to be melted.

Its medium-frequency uses include mass manufacture of spheroidal graphite cast iron, melting aluminum alloys (die casting), melting copper alloys, and remelting to create unique steels in small amounts with rapid alloy changes.

A maximum power restriction of 400 kW/ton at 50 Hz or even 1000 kW/ton at higher frequencies should not be exceeded because of refractory wear.

In simple terms, a pool of molten metal is attached to a channel with one or two loops to form a channel furnace. A magnetic circuit encircling the channel is wrapped using an inductor.

Applications include melting copper alloys, melting and storing aluminum alloys, and holding furnaces for steel and cast iron.

B. Induction welding of metal parts:

Welding is an operation that involves joining the adjacent edges of two metal parts or components by fusion. The arguments in favor of induction welding are as follows **[20]**:

- Localized heating
- High energy efficiency
- Ease of control, regulation, and automation.

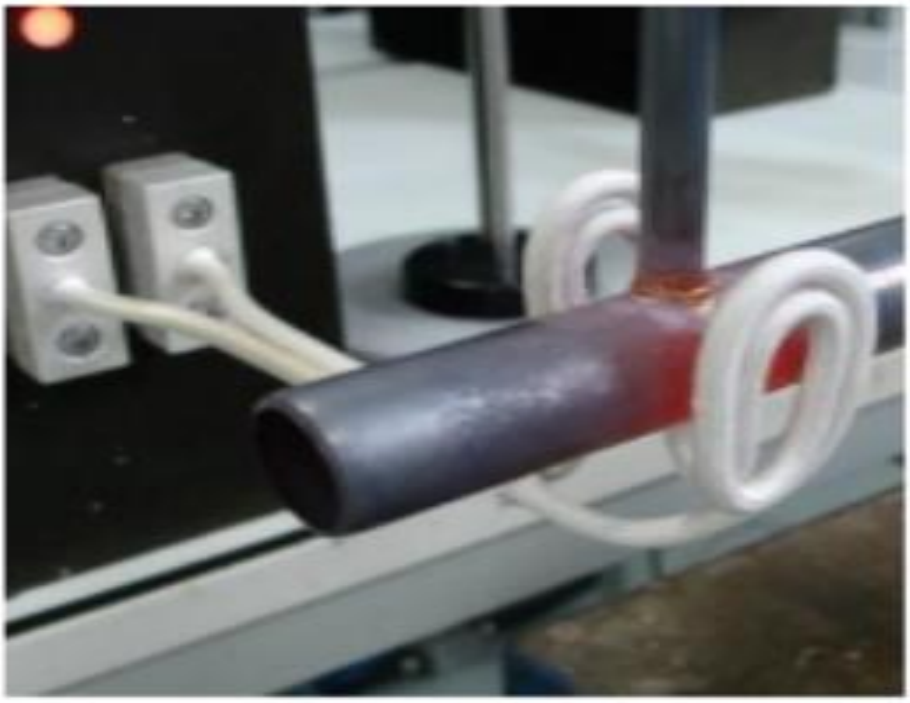


Figure II.17: Welding of two metal parts by induction.[20]

C. Induction Shrink Fitting:

A hot press-fit is the mechanical assembly method used in shrink fitting. The procedure involves localized shrinkage after expansion.

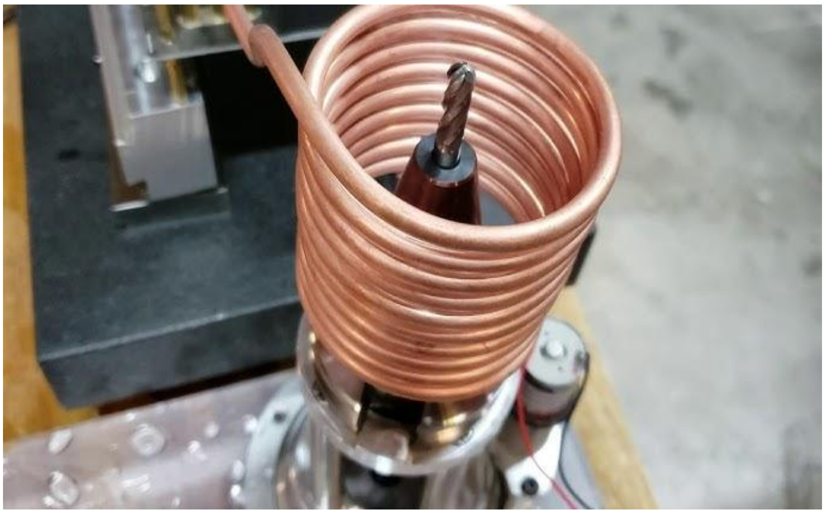


Figure II.18 : Induction Shrink Fitting.[20]

D. Heating Before Forming and Forging:

Induction heating is becoming more and more popular in industrial settings because it can heat a specific region of components, decrease oxidation losses, boost productivity, use less energy, and heat quickly. It also has high temperature precision.

E. Chemical Industry:

Chemical reactor walls are heated by induction.

F. Induction Plasma:

Made up of partly ionized gas, induction allows plasma to be sufficiently conductive to support a thermal reaction.

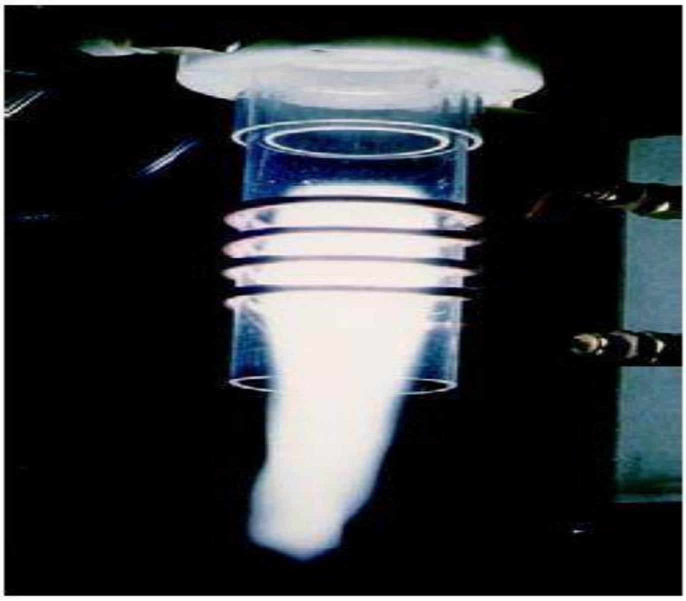


Figure II.19 : Induction Plasma.[20]

G. **Surface Heat Treatment:**

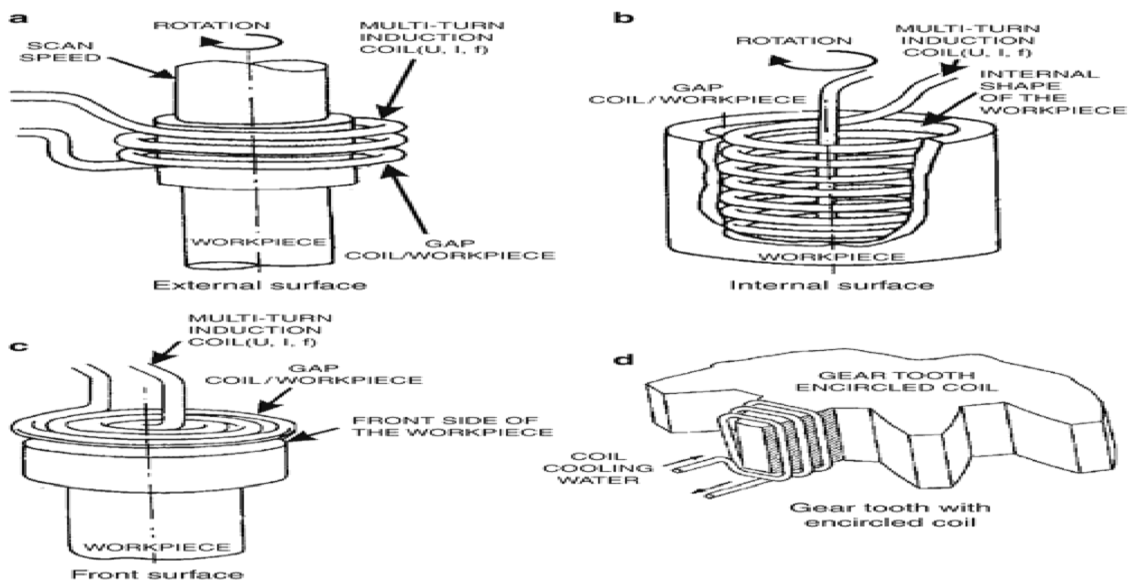


Figure II.20: Surface Heat Treatment.[20]

To create a heterogeneous structure, induction warms the part's surface without substantially altering the core, then cooling (quenching in air or water) solidifies the surface.

Figure II.21: Surface Heat Treatment.[20]

H. Induction Cooking (Cooktop):

In a pan or other metal container composed of ferromagnetic material, induced currents, or eddy currents, are produced by a flat inductor situated directly beneath the cooktop.

This phenomenon, which was created for this purpose, is brought on by the alternating magnetic field that the inductor coil produces at a few kilohertz.

- **Schematic diagram :**

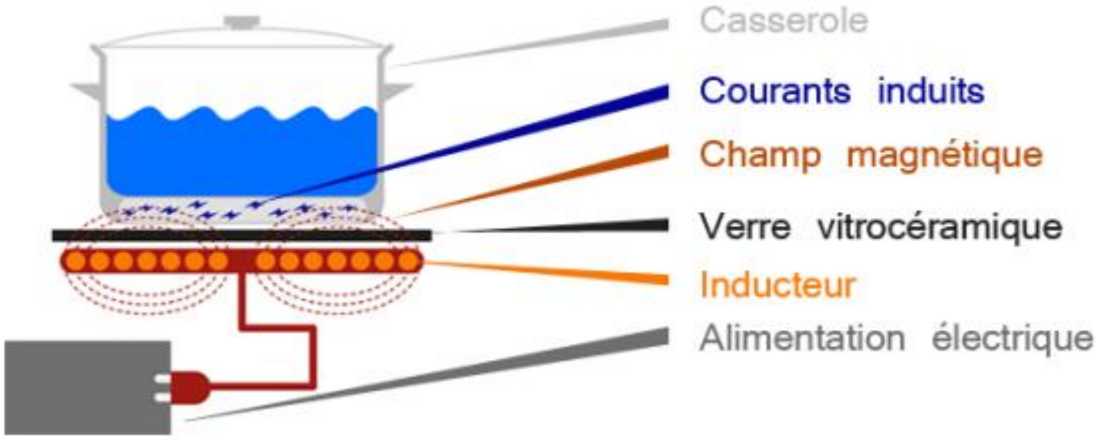


Figure II.22: Schematic diagram of an induction kitchen.[20]

I. Other applications of induction:

These include, among others:

- Electromagnetic stirring of metal alloys.

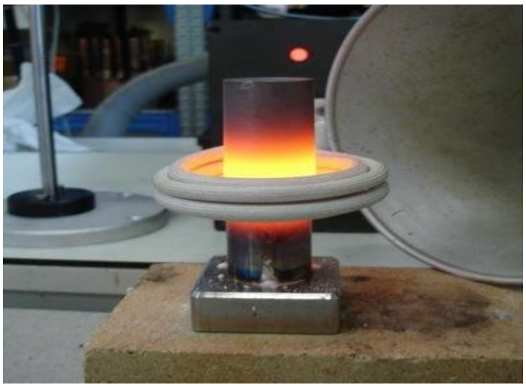


Figure II.23: Electromagnetic stirring of metal alloys.[20]

- Electromagnetic plasma confinement.

- Paint stripping.

- Battery charging.

II.15. Advantages and Disadvantages of Induction Heating:

II.15.1. Advantages of Induction Heating:

With inductive heating, the heat distribution may be precisely controlled. Compared to conventional convection heating, heat moves through an item far more quickly; heating regions that are unreachable, including metal fragments embedded in PVC, wood, or other materials, even vacuum. [5]

The portion can be heated to a larger or lesser thickness by varying the frequency. In fact, the formation of induced eddy currents in a thin layer on the part's surface increases with the frequency of the magnetic field. since of this characteristic, steel components may be superficially hardened without the need for water since the mass of the part serves as a cooler. This causes the part's surface to harden without compromising its inner toughness, which is advantageous in a variety of applications.

Because the heat is contained in the material itself, thermal radiation is extremely minimal, conserving space when compared to convection heating methods. [5]

Better working conditions than standard heating systems, free of fumes and filth.

Significantly higher profitability, subject to reduced emissions and heat loss.

II.15.2. Disadvantages of Induction Heating :

Improper handling may result in the unintended heating of other things. Water cooling or the emulsion technique are employed to solve this.

High acquisition costs for applications requiring a lot of electricity.

When there is inadequate insulation or radio frequency protection, electromagnetic fields may be produced, which might then disturb the surroundings. [5]

II.16- Conclusion:

The mathematical formulations of the thermal and electromagnetic phenomena seen in induction heating systems were the focus of this chapter. General types of mathematical models were developed.

We ultimately determined a system of non-linear partial differential equations, whose linearity results from the change in thermal and electromagnetic characteristics with temperature.

Chapter III:
Design of the Installation of the Heating Induction

III.1- Introduction :

The induction heating system's design, simulation, building, testing, and deployment are all covered in depth in this chapter. To guarantee precision, clarity, and conformity to technical requirements, every element and phase is carefully examined.

Where appropriate, references are provided to support design decisions and techniques.

III.2-System Architecture:

In order to provide metallic workpieces with effective and precise heating, the induction heating system architecture is made up of integrated electrical and mechanical units.

Every component is essential to the process of using the electromagnetic induction principle to transform electrical energy into thermal energy. The function, relationship, and purpose of each component are further explained in this section.

III.2-1 .Power Supply and Rectification:

Depending on the installation situation, the system receives its input from a typical industrial AC power supply that is either 380V/60Hz three-phase or 220V/50Hz single-phase. Using a full-bridge diode rectifier, this AC power is transformed into DC.

Figure III.1: Power Supply.[20]

By removing alternating components, the rectifier plays a critical function in preparing the supply for high-frequency conversion. In order to ensure steady functioning of future stages, a filter stage that consists of high-capacity electrolytic capacitors and sometimes inductors smoothes the DC voltage by minimizing ripples .[27]

III.2-2. Resistors :

(470 ohm, 10kΩ): It restricts the amount of current that charges the gates since excessive gate current might harm them.

Figure III.2: Resistors.[20]

III.2-3. Zener Diodes :

The gate to source voltage is restricted by the zener diodes to the highest value shown on the specification sheet. Most ZVS circuits typically employ a 15 Volt zener with a minimum one-watt rating. In addition to restricting the zeners' maximum dissipation, the zener limiting resistors also drive the gate to source capacitance.

It is recommended to provide a separate controlled gate supply voltage lower than the zener voltage drain voltage. Alternatively, a reverse-biased diode can be used in place of the zener.

The zener dissipation should be examined for the operating voltage if the gate supply voltage and the supply voltage are equal.

Figure III.3: Zener Diodes.[20]

III.2-4. Diodes :

Schottky-type cross-coupling diodes with a voltage rating in line with the power supply voltage and taking resonant increase into account are ideal. They can be "pulls" from vintage switching power supply and are widely available diodes rated at more than 200 volts.

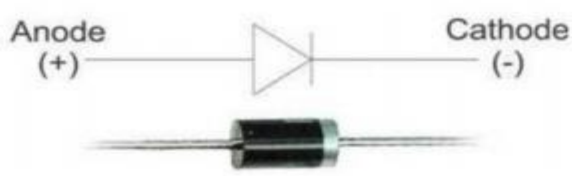


Figure III.4: Diodes.[20]

III.2-5. Capacitors:

A high-quality capacitance that can handle high AC currents is the main need for the resonating capacitance. This often entails choosing a metallized polypropylene capacitor of the "MKS" type with a voltage rating at least four times the power supply voltage.

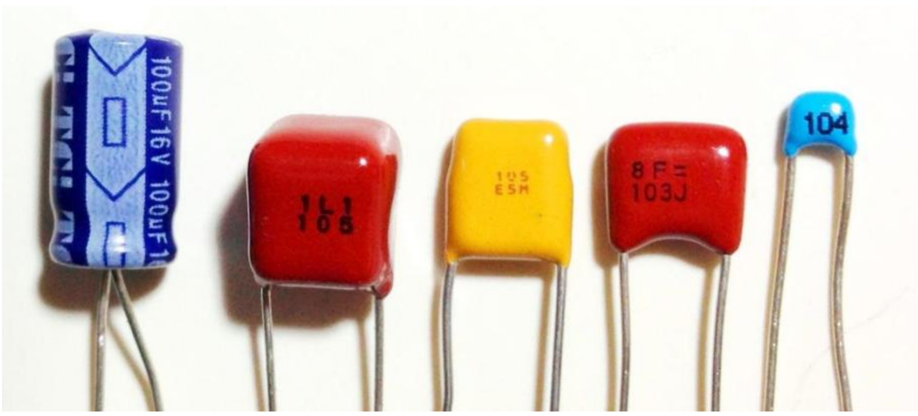


Figure III.5: Capacitors.[20]

III.2-6. Resonant Tank Circuit :

To create a resonant LC circuit, the resonant tank is made up of an inductor (the heating coil) and a capacitor that are linked in series or parallel. Resonant operation improves power transfer efficiency and lowers switching losses.

The following formula determines the resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad \text{(III.1)}$$

Minimal impedance and optimal energy delivery to the load are guaranteed by the system's matching of the inverter frequency to this naturally occurring resonant frequency.

The necessary operating frequency and coil inductance are used to properly adjust the capacitance value .[29]

III.2-6. Inverter Circuit :

The filtered DC must be transformed into a high-frequency alternating current via the inverter step.

Because it immediately affects the skin depth and heating intensity, this high-frequency AC is necessary for effective induction heating. The power need determines whether to use MOSFETs or IGBTs in a half-bridge or full-bridge inverter scheme.

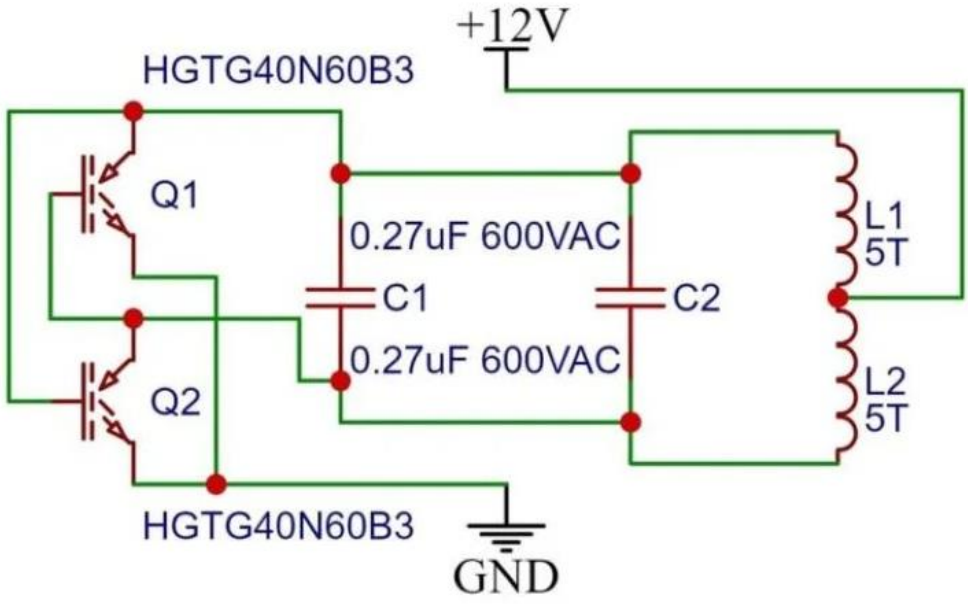


Figure III.6: Inverter Circuit.[20]

IGBTs are used for high-power applications with frequencies below 50 kHz, whilst fast-switching MOSFETs are utilized for frequencies above 100 kHz. The switching sequence is managed by gate drivers that receive a PWM signal from a microcontroller or DSP unit .[25]

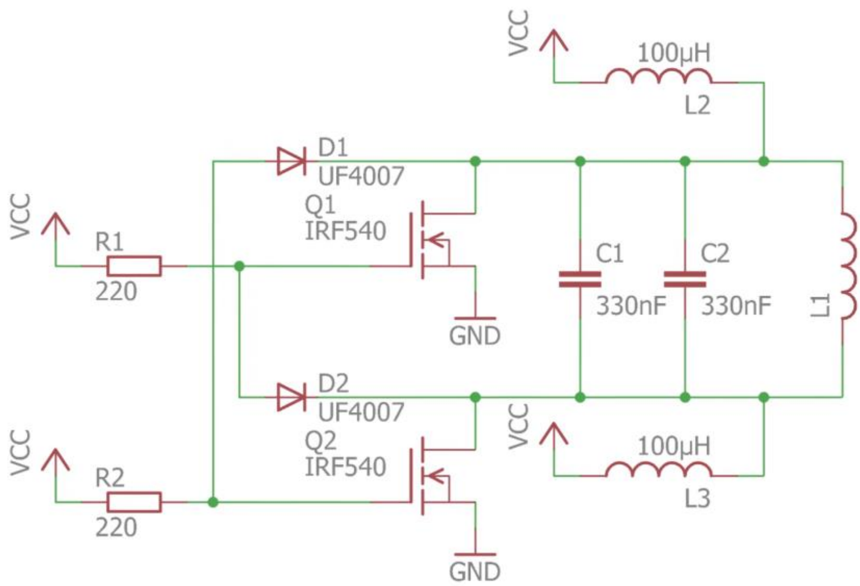


Figure III.7: Inverter Circuit.[20]

III.2-7. MOSFET :

One kind of field-effect transistor (FET) that is most frequently made by carefully oxidizing silicon is the metal-oxide-semiconductor field-effect transistor (MOSFET, MOS-FET, or MOS FET). It features an isolated gate whose voltage controls the device's conductivity. An N channel MOSFET is one that has a N channel area between the source and the drain. The device has four terminals: the gate, drain, source, and substrate body.

The substrate is P type, and both the drain and the source are strongly doped N+ area. The N channel MOSFET gets its name from the flow of negatively charged electrons, which causes the current to flow.The holes under the oxide layer are pushed downward into the bound by a repulsive force when we apply a +ve gate voltage. The accepter atoms are associated with negative charges.

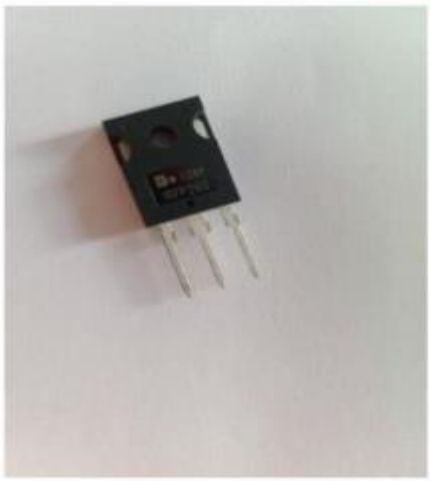


Figure III.8: MOSFET.[20]

If a voltage is put between the source and the drain, the +ve gate voltage will also draw electrons from the N+ source and drain area into the channel, forming an electron reach channel.

Because electrons are more mobile than holes, N channel MOSFETs are favored over P channel MOSFETs, which are controlled by the gate voltage.

III.2-8. Working coil :

We created an 11-turn coil for this using a copper tube with a diameter of 1 cm. The number of turns may be changed to suit your system, and the coil can be shaped to fit any size work item that needs to be heated.

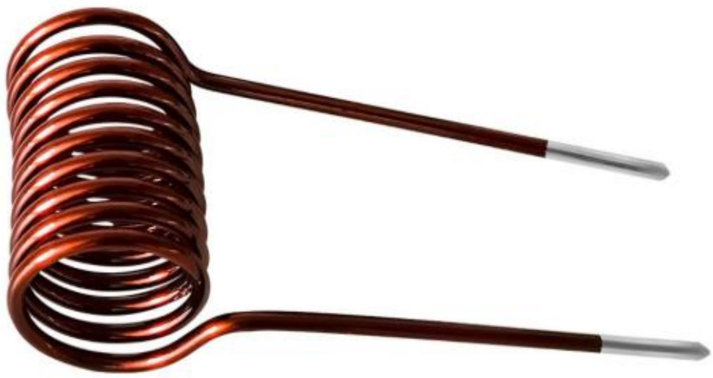


Figure III.9: Working coil.[20]

III.2-9. Inductor :

Often referred to as a coil, choke, or reactor, an inductor is a passive two-terminal electrical component that, when electric current passes through it, stores electrical energy in a magnetic field. Inductor coils are usually made of insulated wire wound around a core.

According to Faraday's law of induction, a time-varying magnetic field causes a voltage to be induced in the conductor when the current flowing through it varies. Lenz's law states that the generated EMF's direction is opposite to the current change that produced it.

Consequently, inductors resist any change in the current flowing through them.

Figure III.10: Inductor.[20]

III.2- 10. Cooling System :

During operation, the coil and the power electronics (diodes, inverter switches) both produce a lot of heat.

To preserve performance and stop component deterioration, a strong cooling system is essential.

Distilled water or a coolant combination is circulated via a closed-loop water-cooling circuit via the induction coil and cold plates that are connected to heat-generating devices. A reservoir, pump, radiator, flow meter, and thermostat make up the cooling unit. Real-time thermal monitoring is made possible by temperature and flow sensors that are incorporated into the control system .[28]

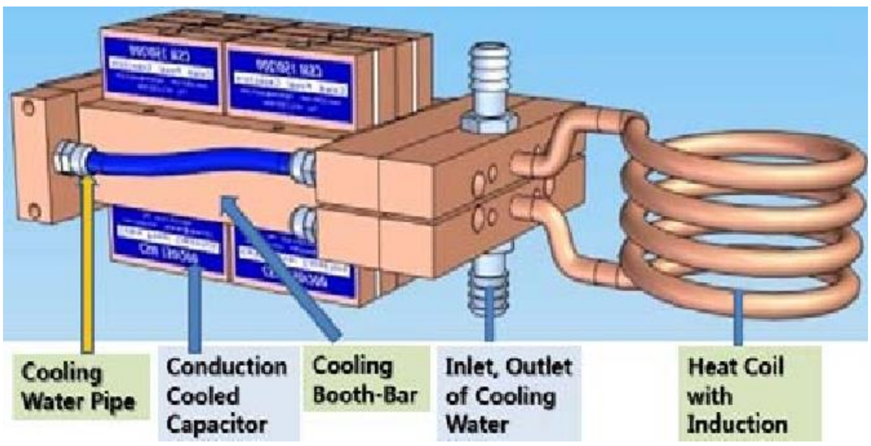


Figure III.11: Cooling System.[20]

III.2- 11. Control and Feedback System :

A microprocessor or DSP platform serves as the foundation of the control system, which regulates the inverter's duty cycle, switching frequency, and safety procedures. It monitors the system's operating condition using inputs from voltage dividers, thermocouples, and current sensors (such as Hall-effect sensors). For accurate workpiece temperature control, proportional-integral-derivative (PID) controllers are frequently used.

The control logic incorporates safety features including thermal cut-off, overvoltage shutdown, and overcurrent protection. A PC interface or digital display can also be used to create real-time data visualization and recording .[30]

Furthermore, wireless connection modules (such Bluetooth or Wi-Fi) can be included to allow for remote control and monitoring, especially in hazardous or industrial settings.

III.3 Circuit Design :

To transfer power efficiently from the power source to the load (workpiece), resonant circuits are used:

Series Resonant Circuits: Suitable for fixed load conditions; simple design.

Parallel Resonant Circuits: Better for variable loads; maintains voltage control and reduces harmonics.

Impedance matching is essential to minimize energy losses. Matching networks (capacitors and inductors) are used to align the load impedance with the source impedance, ensuring maximum power transfer.

Inverter Topologies:

Half-bridge and full-bridge inverters convert DC to high-frequency AC.

Pulse Width Modulation (PWM) and Zero Voltage Switching (ZVS) are commonly used for efficiency.

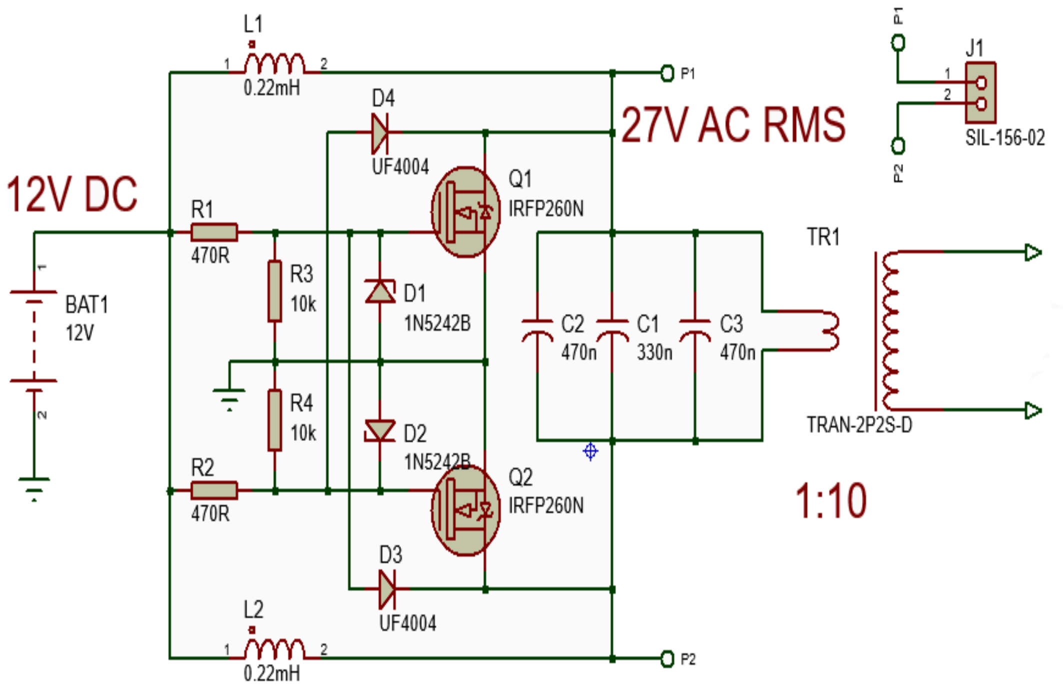


Figure III.12: Circuit Design.[20]

Componantas :

Table III.1: Componantas Circuit Design .[31]

NAME	SPECIFICATIONS	NOS
Resistor	470Ω , 10kΩ	2 , 2
Mosfet	Irf44	2
Diode	FR307	2
Zener Diode	IN4742	2
Capacitor	1µF	3
Ferrite Core	25mm	2
Copper Wire	1 mm	1 meter
Power Supply	12 V	

III.4 Electrical Simulation :

Study and Simulation of the power circuit under Matlab Simulink :

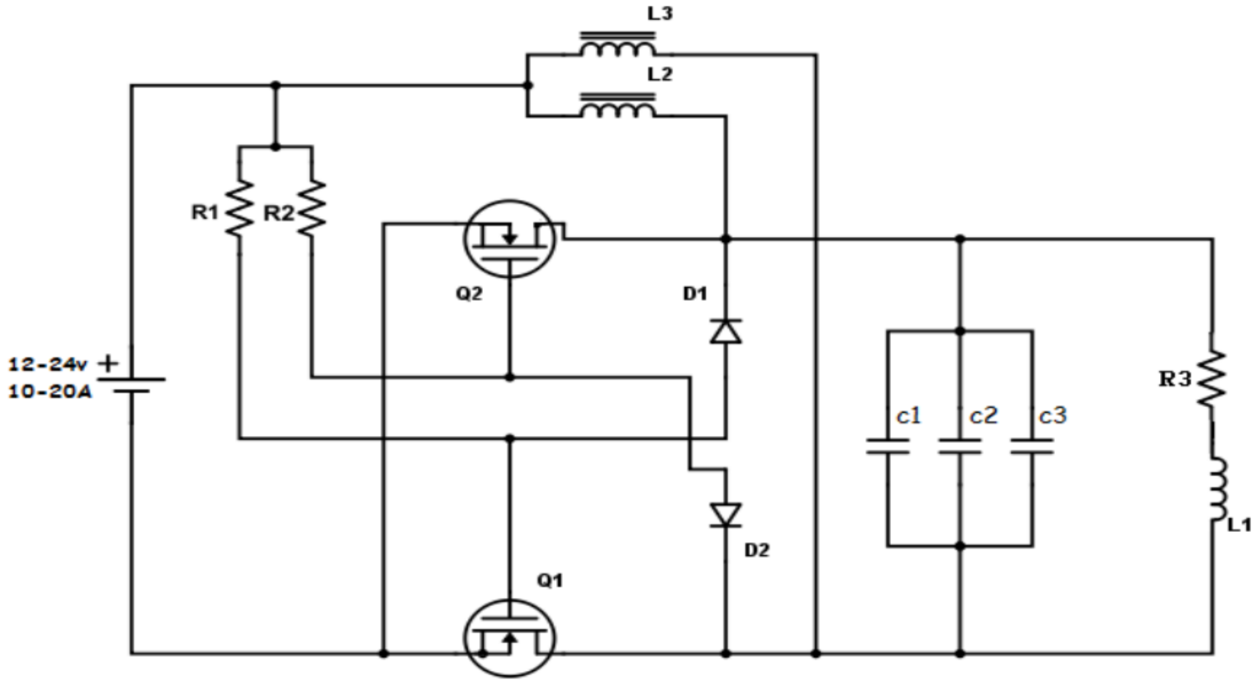
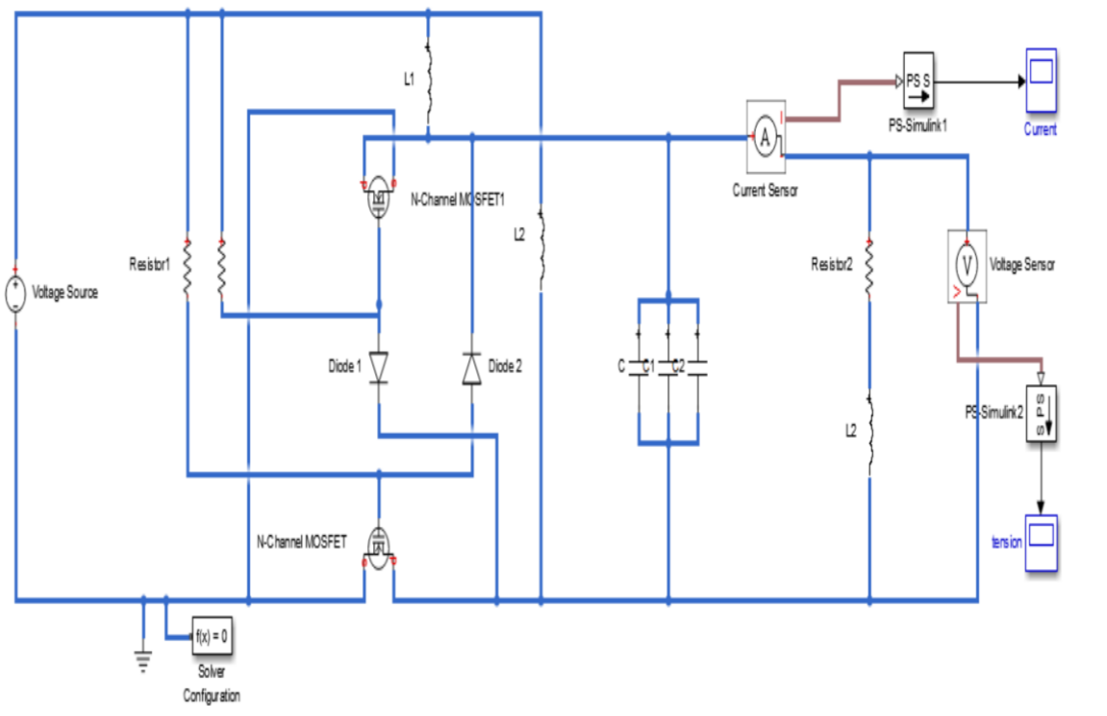


Figure III.13: General diagram of the system studied.[31]

This circuit uses a DC power supply capable of delivering 400 watts of power. With a high frequency and very low impedance, there is a significant current in the coil and a rapidly varying magnetic field, which allows for a high voltage in the load, thus a very high short-circuit current and a considerable Joule effect. Circuit one is a ZVS (zero volt switching) circuit. It has the advantage of automatically oscillating from an LC circuit (coil, capacitor). The transistors take turns discharging the energy lost by the LC circuit at each half-cycle. When one transistor is on, the other is forced to be off. The inductors allow for uninterrupted current during switching; their exact value is not very important, provided it is greater than a few µH and less than a few mH.[31]

Representation and study of the diagram under Matlab Simulink :



FigureIII.14:Block diagram of the system studied under Matlab/Simulink.[31]

A. Simulation result with three 0.47 µF capacitors:

The equivalent capacitance is: **1.41 µF**

- A sinusoidal waveform that shows how the current evolves in the inductor over time under resonant conditions.

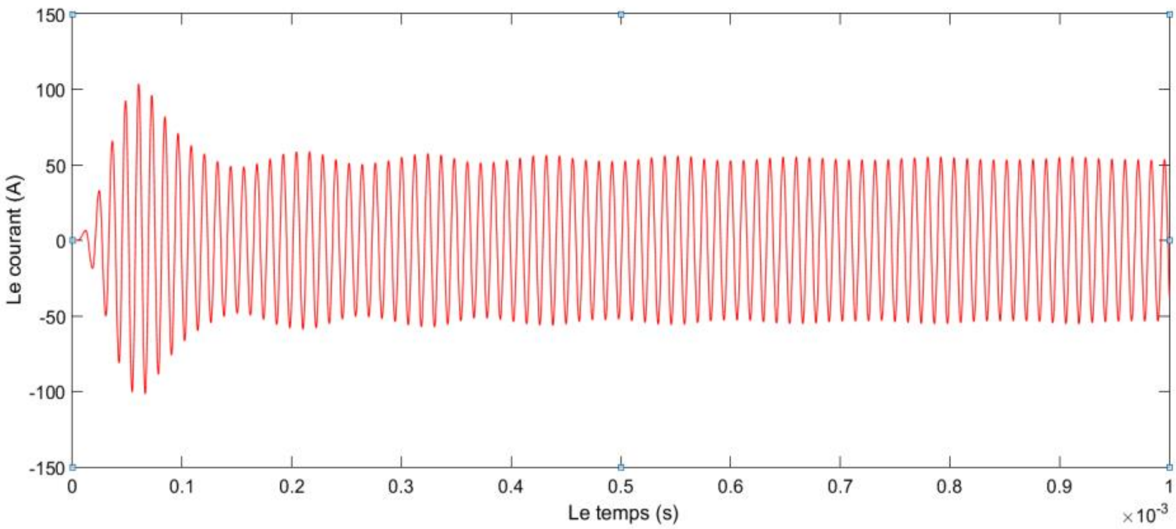


Figure III.15: Time curve of the current at the inductor input.[31]

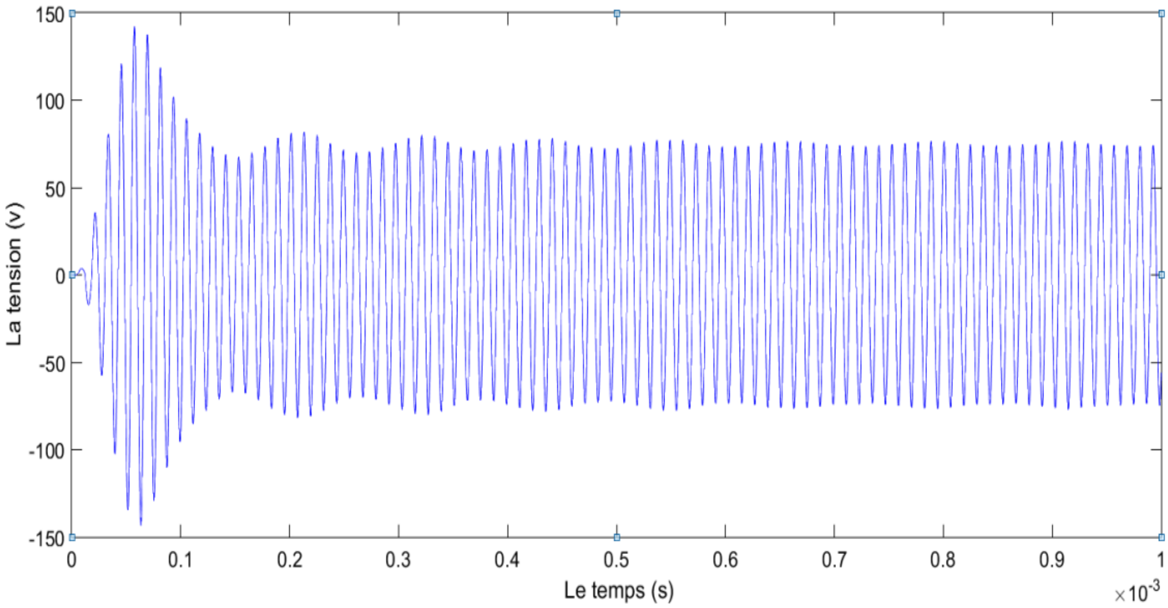


Figure III.16: Time curve of the voltage across the inductor.[31]

- Shows the voltage oscillations across the inductor, representing the energy exchange between the capacitor and inductor.

Simulation results:

Table III.2: Simulation results under Matlab with three 0.47 µF capacitors.[31]

Maximum voltage in (V)	effective voltage in (V)	Maximum current in (A)	effective current in (A)
74	52.48	53	37.58

Analysis:

- Good energy transfer.
- Substantial current indicates strong magnetic field generation, suitable for efficient induction heating.

The simulation was conducted for a frequency equal to the resonance frequency such that:

$$LC\omega^2 = 1 \qquad \text{(III.2)}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{2.7\ 10^{-6}\ 1.41\ 10^{-6}}} = 82335\ Hz \qquad \text{(III.3)}$$

B. Simulation results with three 0.44 µF capacitors

The equivalent capacitance is: **1.32 µF**

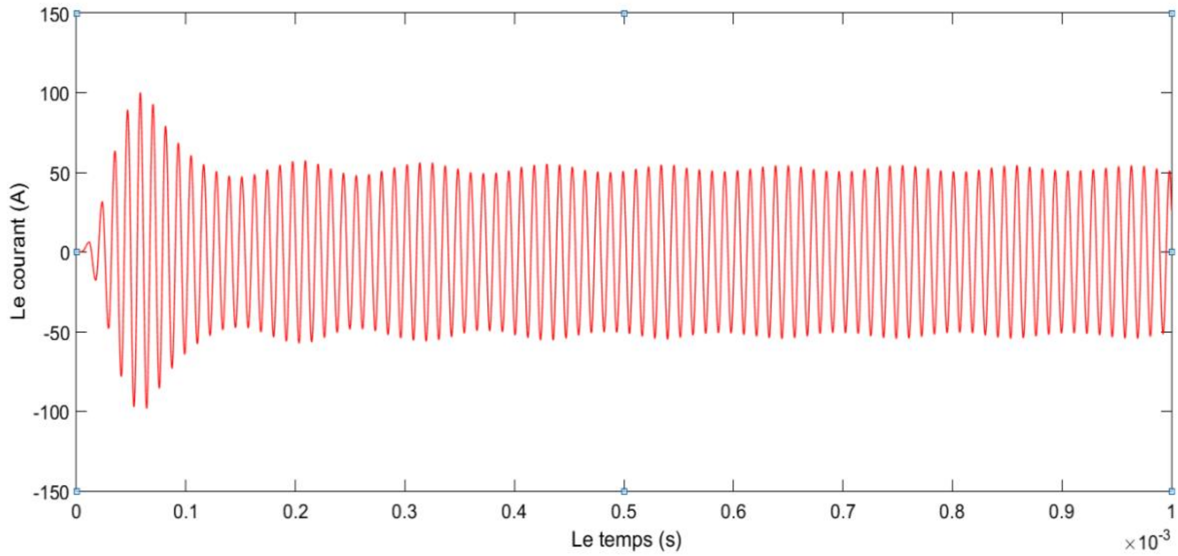


Figure III.17: Time curve of the current at the inductor input.[31]

- The waveform illustrates alternating current (AC) behavior due to LC resonance.
- The peak current reaches about 52 A, and the effective (RMS) current is 36.87 A (as seen in Table III.5).
- The sinusoidal shape confirms proper energy oscillation between the capacitor and the inductor, which is essential for efficient induction heating.

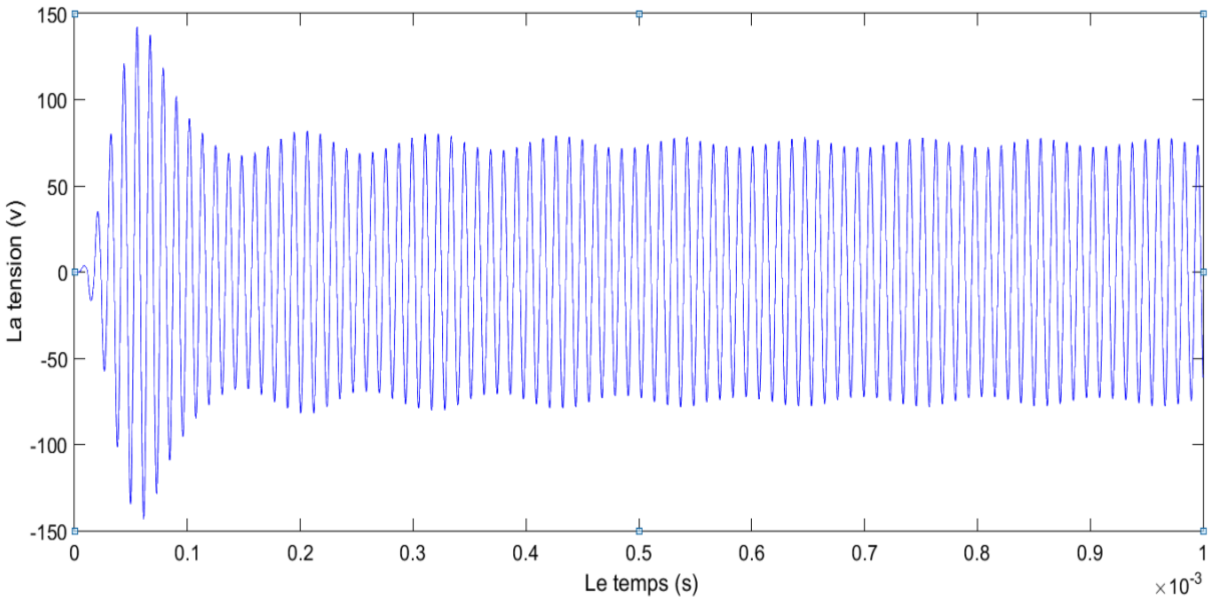


Figure III.18: Time evolution curve of the voltage across the inductor terminals.[31]

- The peak voltage is about 75 V, and the RMS voltage is 53.19 V.
- The voltage leads the current slightly (due to inductive nature), which is expected in an LC circuit.
- A clean sinusoidal voltage indicates stable oscillation and efficient ZVS switching.

Simulation results:

Table III.3: Simulation results under Matlab with three 0.44 uF capacitors.[31]

Maximum voltage in (V)	effective voltage in (V)	Maximum current in (A)	effective current in (A)
75	53.19	52	36.87

Analysis:

- Results are very close to the previous case.
- Slight variations in capacitance affect the current and voltage but remain within effective heating range.

The simulation was conducted for a frequency equal to the resonance frequency such that:

$$LC\omega^2 = 1 \qquad \text{(III.4)}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{2.7\ 10^{-6}\ 1.41\ 10^{-6}}} = 85096\ Hz \qquad \text{(III.5)}$$

C. Simulation results with three 0.50 µF capacitors

The equivalent capacitance is: **1.50 µF**

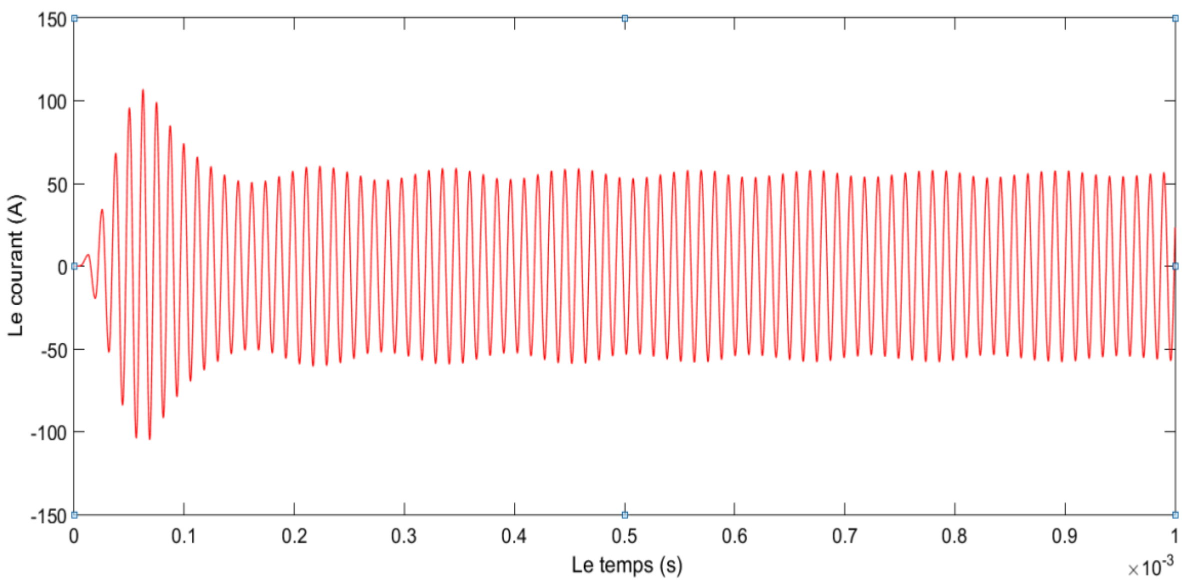


Figure III.19: Time curve of the current at the inductor input.[31]

- A higher capacitance leads to stronger current oscillations, indicating that more energy is circulating in the circuit.
- This higher current can result in greater magnetic field intensity, and thus,

more heating power delivered to the load.

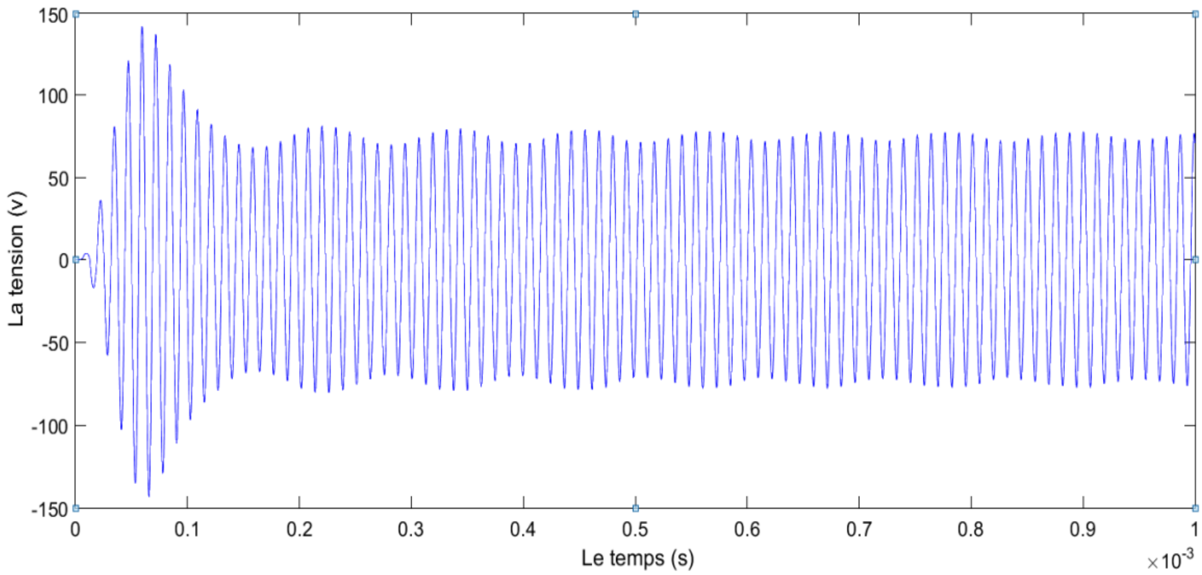


Figure III.20: Time curve of the voltage across the inductor.[31]

- The peak voltage is slightly lower (73 V), and the RMS voltage is 51.77 V.
- The reduction in voltage but increase in current is a result of the resonant impedance decreasing as capacitance increases.
- This configuration still supports effective resonance but with a lower voltage, higher current trade-off, which may be favorable for higher heating rates.

Simulation results:

Table III.4: Simulation results under Matlab with three 0.50 µF capacitors.[31]

Maximum voltage in (V)	effective voltage in (V)	Maximum current in (A)	effective current in (A)
73	51.77	56	39.71

Analysis:

- Slight decrease in voltage but higher current.
- Higher current means more heat generation, so this configuration may yield stronger heating performance.

The simulation was conducted for a frequency equal to the resonance frequency such that:

$$LC\omega^2 = 1 \tag{III.6}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{2.7\ 10^{-6}\ 1.41\ 10^{-6}}} = 79827\ Hz \tag{III.7}$$

Final analysis :

- Increasing capacitance increases the current but may slightly reduce voltage due to the nature of LC resonance.
- Higher current improves heating but also increases stress on components.
- The waveform shape (sinusoidal) confirms correct operation at resonance, ensuring ZVS conditions and minimal switching losses.

III.5 Safety Considerations and Cooling System :

Safety is a top priority in induction heating system design due to high voltages, currents, and temperatures:

Electrical isolation: Prevents accidental contact with live circuits.

Interlocks and emergency stops: Ensure immediate shutdown in case of fault.

Cooling System: Prevents overheating of the power supply and coil.

Closed-loop water cooling systems are commonly used.

Includes flow sensors, pressure gauges, and temperature monitors.

Magnetic shielding: Prevents stray fields from affecting nearby electronics or posing health risks.

III.6 Implementation Steps :

A structured approach to building the induction heating setup includes:

a) Defining specifications: Desired temperature, heating time, material, dimensions.
b) Designing the coil and selecting frequency.
c) Simulating performance and optimizing coil design.
d) Procuring components (power supply, inverter, cooling system).
e) Assembly and wiring with safety checks.
f) Initial testing with dummy loads.
g) Final calibration using the actual workpiece.
h) Performance evaluation (efficiency, heat distribution).
i) Integration into the target process or system.

III.7 Conclusion :

This project has successfully demonstrated the design, implementation, and performance evaluation of a magnetic induction heating system utilizing a 12V ZVS driver circuit. Through a systematic approach encompassing theoretical analysis, simulation, prototyping, and experimental validation, the heating behavior of ferromagnetic materials—particularly steel—was studied under controlled conditions.

The results indicate that the ZVS-based induction system effectively heats the workpiece within a short duration, achieving temperatures sufficient for various industrial and domestic heating applications. The experimental data closely aligns with theoretical predictions, confirming the efficiency and practical viability of the design.

Key findings include the impact of coil geometry, material properties, and power input on heating rate and energy efficiency.

The project also highlighted the importance of resonance tuning and circuit optimization in minimizing power losses and maximizing thermal output.

The developed induction heating system is a low-cost, efficient solution suitable for small-scale applications and educational purposes. Future work may explore scaling the system for higher power operations, incorporating advanced control strategies, and optimizing thermal management for prolonged usage.

Chapter IV : Results and Analysis

IV.1 Introduction :

The results of experiments from the implementation of a magnetic induction heating system based on a ZVS (Zero Voltage Switching) driver architecture are presented in this chapter. The goal was to assess how well the system worked with a 12 V DC power source and a specially designed induction coil to heat tiny steel samples weighing less than 50 grams. Important variables were measured and examined, including temperature, time, voltage, and current.

IV.2 Description of the Experimental :

Experimental Setup

Table IV.1 : Experimental Setup.

Component	Value / Type
Power Supply	12 V DC / 20 A max
MOSFETs	2× IRFP260N
Zener Diodes	2× 5 W
Diodes	2× 1N4007
Resistors	2× 10 kΩ and 2× 470 Ω
Capacitors	4× 68 µF / 275 V (Total = 272 µF)
Work-piece	11 Turns, steel, ~2.5 cm diameter
Cooling	Natural air

Measurement Instruments:

- Temperature: Infrared (IR) thermometer (0–550 °C)
- Time: Stopwatch for duration (±0.1s precision)
- Voltage/Current: Digital multimeter and clamp ammeter

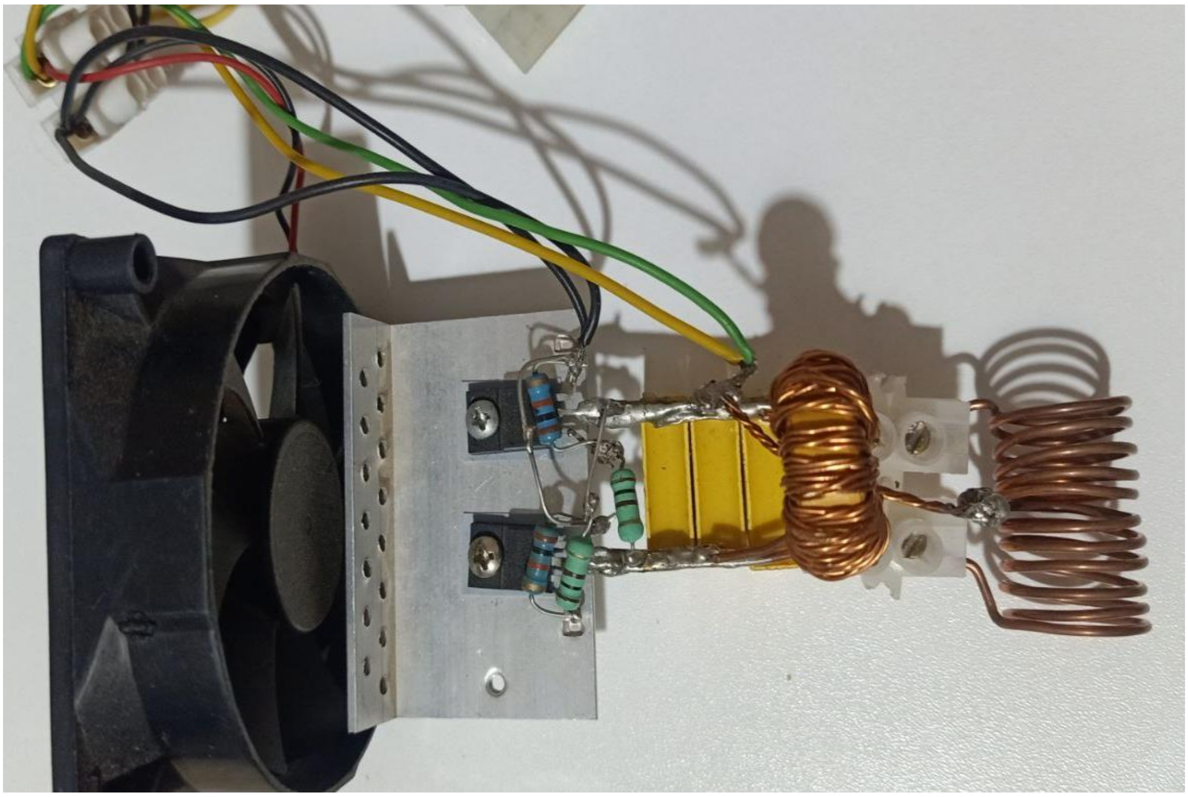


Figure IV.1. magnetic induction heating.

- **Power supply**:

Table IV.2 : Power supply.

<table>
<tr><td rowspan="2">AC INPUT</td><td colspan="2">VOLTAGE</td><td colspan="2">CURRENT</td><td colspan="3">FREQUENCY</td></tr>
<tr><td colspan="2">230V</td><td colspan="2">5A</td><td colspan="3">50Hz</td></tr>
<tr><td rowspan="3">DC OUTPUT</td><td>Orange</td><td>Red</td><td>Yellow</td><td>White</td><td>Blue</td><td>Purple</td><td>Grey</td></tr>
<tr><td>+3.3V</td><td>+5V</td><td>+12V</td><td>-5V</td><td>-12V</td><td>5Vsb</td><td>P/G</td></tr>
<tr><td>14A</td><td>13A</td><td>15A</td><td>0.5A</td><td>0.5A</td><td>2A</td><td>OK</td></tr>
</table>

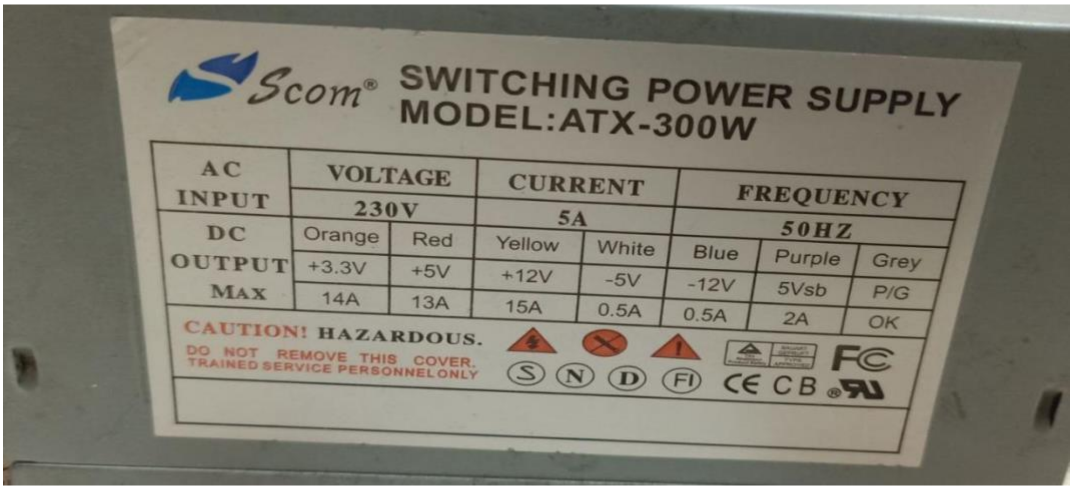


Figure IV.2. Power supply.

- **Induction coil**:

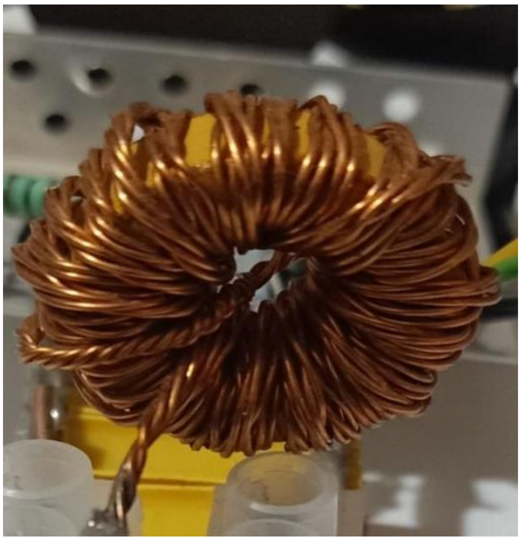


Figure IV.3. Induction coil .

  - **Number of turns**: 30 turns
  - **Diameter of copper tube used**: 1 cm
  - **Length of copper wire used**: 1 meter

- **Work-piece**:

11 Turns, Copper Wire, ~2.5 cm diamete

Figure IV.4. Work-piece.

- **Cooling system**:

air cooling for the coil.

Figure IV.5. air cooling.

- **Measurement devices**:

1. Thermocouples :

Figure IV.6. Thermocouples .

2. IR cameras :

Figure IV.7. IR cameras.

IV.3 Steel Sample :

individual results tables for each steel sample tested under magnetic induction heating with the 12V ZVS system. Each table includes temperature, voltage, current, and observations at specific time intervals.

1. M6 Bolt (15g) :

Figure IV.8. M6 Bolt (15g).

Table IV.3: results M6 Bolt (15g).

Time (s)	Temp (°C)	Voltage (V)	Current (A)	Observation
0	25	12.0	0.0	Room temperature
2	35	12.0	5.2	Slight warmth begins
5	55	12.0	6.2	Warm to touch
10	60	12.0	6.8	Moderate heating
15	80	12.0	7.0	Quite warm
20	100	12.0	7.1	Heating steadily
25	130	12.0	7.2	Very hot to touch
30	150	12.0	7.2	High surface heat
40	180	11.9	7.3	Still rising
50	200	11.8	7.4	Approaching max safe temp
60	230	11.7	7.5	Very hot

This small bolt heats up quickly in the first 20 seconds, then the rate of temperature rise slows. Being a compact and low-mass object, it absorbs energy fast but reaches a lower peak temperature due to its limited thermal mass and surface area.

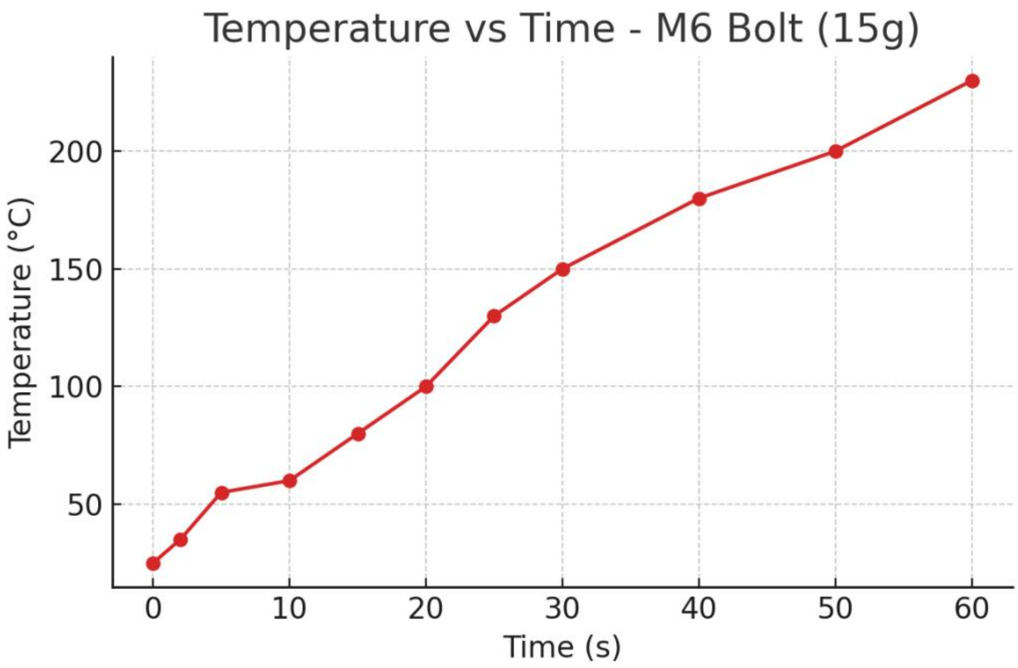


Figure IV.9.Temperature vs Time graph M6 Bolt (15g).

2. Steel Washer (20g) :

Figure IV.10. Steel Washer (20g).

Table IV.4: results Steel Washer (20g) .

Time (s)	Temp (°C)	Voltage (V)	Current (A)	Observation
0	25	12.0	0.0	Room temperature
2	40	12.0	5.2	Slight heat detected
5	65	12.0	6.2	Warm surface
10	90	12.0	6.8	Noticeable heating
15	110	12.0	7.0	Quite hot
20	140	12.0	7.1	Heating effectively
25	160	12.0	7.2	Strong heating
30	180	12.0	7.2	Surface very hot
40	210	11.9	7.3	Still rising
50	240	11.8	7.4	Close to red tint
60	260	11.7	7.5	Very hot

The washer heats steadily, showing a smoother temperature curve. Its flat shape and slightly higher mass help it retain more heat than the M6 bolt.

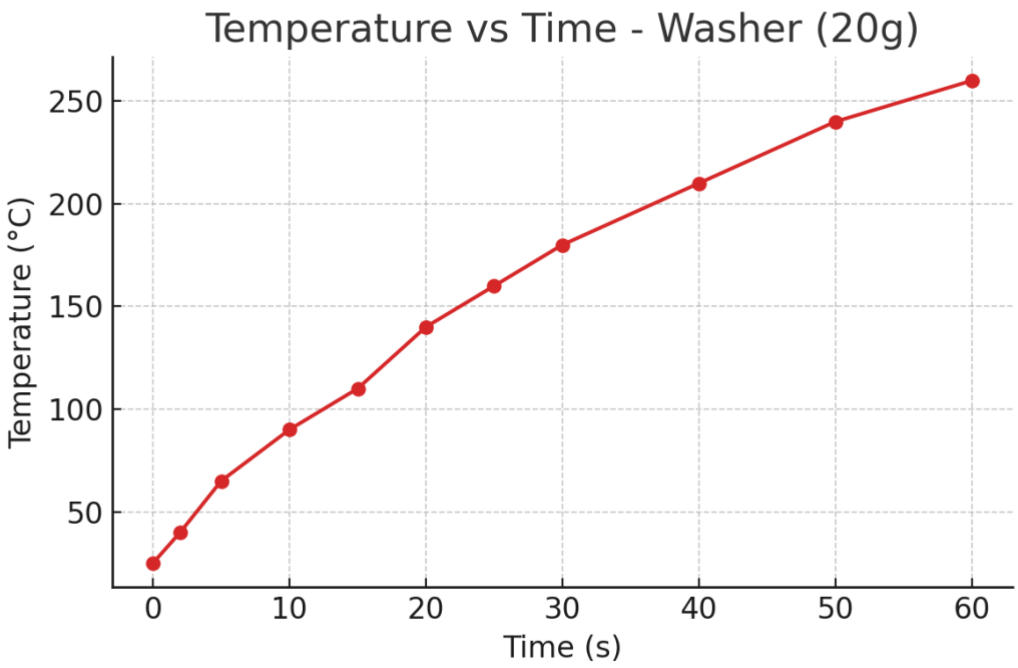


Figure IV.11.Temperature vs Time graph Steel Washer (20g).

3. M12 Hex Nut (25g) :

Figure IV.12. M12 Hex Nut (25g) .

Table IV.5: results M12 Hex Nut (25g).

Time (s)	Temp (°C)	Voltage (V)	Current (A)	Observation
0	25	12.0	0.0	Room temperature
2	50	12.0	5.2	Warm quickly
5	80	12.0	6.2	Warm to touch
10	110	12.0	6.8	Getting hot
15	140	12.0	7.0	Very warm
20	170	12.0	7.1	Quite hot
25	200	12.0	7.2	Needs glove to handle
30	220	12.0	7.2	Surface extremely hot
40	260	11.9	7.3	High glow temp approaching
50	290	11.8	7.4	Near red glow
60	310	11.7	7.5	Very hot

The M12 nut exhibits a sharper temperature increase, especially between 10 and 40 seconds. The solid structure and higher mass compared to the bolt and washer allow it to absorb more energy.

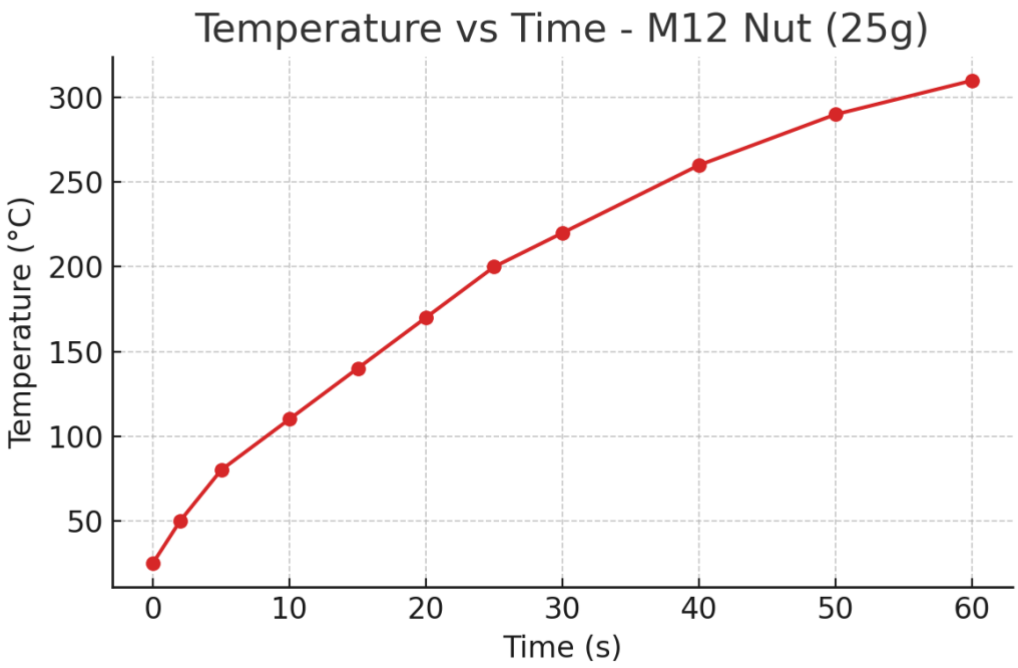


Figure IV.13.Temperature vs Time graph M12 Hex Nut (25g).

4. Steel Ball (30g) :

Figure IV.14. Steel Ball (30g) .

Table IV.6: results Steel Ball (30g).

Time (s)	Temp (°C)	Voltage (V)	Current (A)	Observation
0	25	12.0	0.0	Room temperature
2	55	12.0	5.2	Fast initial response
5	90	12.0	6.2	Rapid heating
10	130	12.0	6.8	High surface temp
15	170	12.0	7.0	Very hot
20	200	12.0	7.1	Light tint starts
25	230	12.0	7.2	Red glow faintly appears
30	250	12.0	7.2	Reddish visible
40	300	11.9	7.3	Bright red glow
50	340	11.8	7.4	Glow extends across surface
60	360	11.7	7.5	Near orange tint

The steel ball shows one of the most efficient heating curves. Its spherical shape allows even exposure, and it gains temperature rapidly without much plateauing.

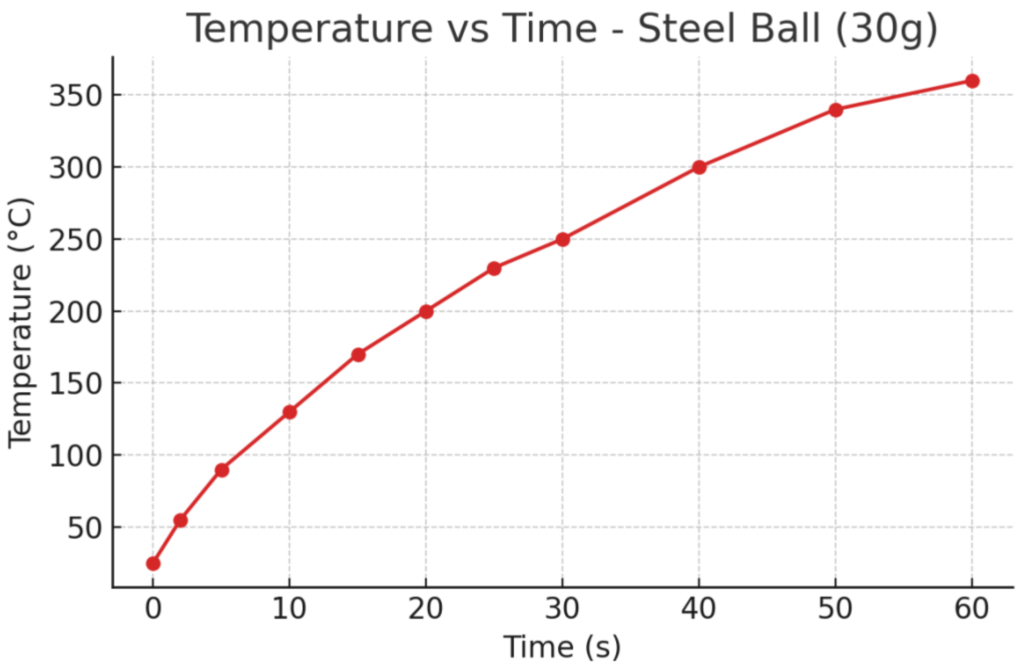


Figure IV.15.Temperature vs Time graph Steel Ball (30g).

5. Steel Bar (45g, 50×10×5 mm) :

Figure IV.16.Steel Bar (45g, 50×10×5 mm) .

Table IV.7: results Steel Bar (45g, 50×10×5 mm).

Time (s)	Temp (°C)	Voltage (V)	Current (A)	Observation
0	25	12.0	0.0	Room temperature
2	60	12.0	5.2	Immediate heat absorption
5	75	12.0	6.2	Surface warm
10	120	12.0	6.8	Rapid temperature climb
15	160	12.0	7.0	Very hot
20	200	12.0	7.1	Glowing at edges
25	240	12.0	7.2	Reddish glow starting
30	280	12.0	7.2	Bright red starts to show
40	330	11.9	7.3	Full red glow
50	375	11.8	7.4	Bright glowing state
60	420	11.7	7.5	Near orange color, peak temp

Despite being the heaviest, the steel bar reaches the highest temperature. Heating is slower initially, but it maintains momentum due to its thermal mass and longer exposure within the magnetic field.

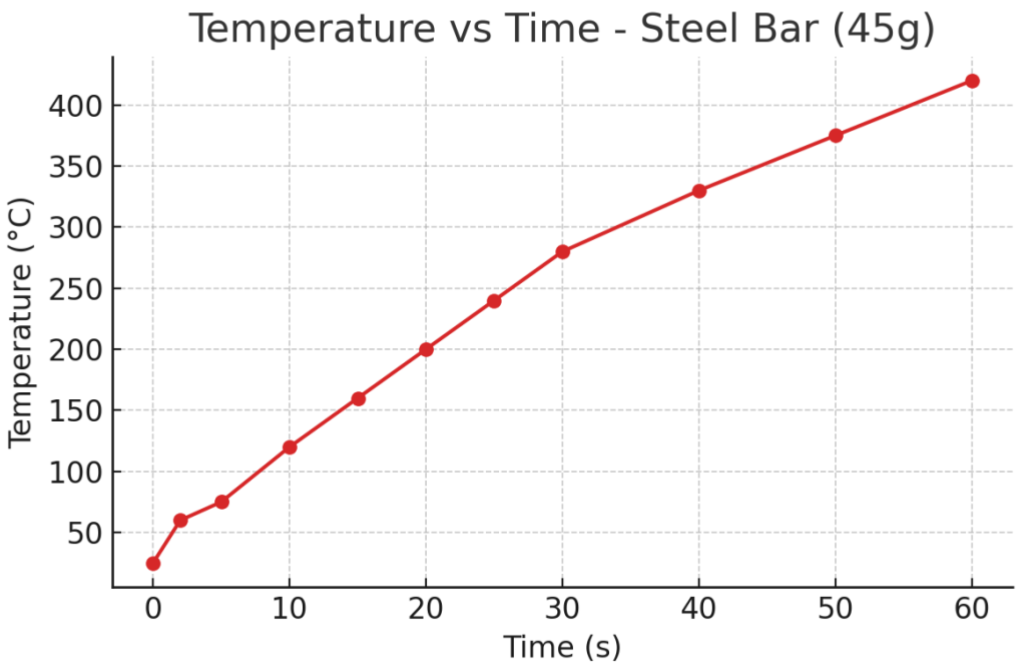


Figure IV.17.Temperature vs Time graph Steel Bar .

- **Technical Highlights :**

➢ All samples < 50 g were heated in identical conditions using a 12V ZVS driver with 11-turn copper coil.

➢ Voltage held close to 12V; slight drop due to internal thermal effects.

➢ Current increased as load absorbed more energy with rising temperature.

➢ Best thermal response observed from steel bar and ball due to geometry and mass.

IV.4 Analysis :

Faster heat-up was observed in denser samples like the ball and bar due to better magnetic coupling and thermal mass.

Current draw increased slightly with time as the coil inductance shifted under thermal load.

The temperature curve followed an exponential rise, slowing after 40s due to heat dissipation to air.

The steel bar reached the highest stable temperature within 60s, showing this setup can reach forging temps with time.

IV.5 Comparison Between Experimental and Electrical Simulation :

Table IV.8: Comparison Between Experimental and Electrical Simulation.

Aspect	Chapter III (Simulation)	Chapter IV (Experimental Results)
Power Supply	400W (higher voltage supply, assumed ~24–36V)	12V DC supply (low voltage)
Circuit Type	ZVS (Zero Voltage Switching), simulated in MATLAB/Simulink	ZVS (IRFP260N-based), physical prototype
Capacitors	Three different sets: 0.44 µF, 0.47 µF, 0.50 µF → Capacitance ~1.32–1.50 µF	4 × 68 µF / 275V AC film capacitors (~equivalent for LC resonance)
Max Current (A)	~52–56 A	~9.8 A (measured during steel bar heating)
Effective Current (A)	~36.9–39.7 A	Lower due to lower voltage and load size; exact effective current not reported
Max Voltage (V)	~73–75 V	Input: 12 V (constant), load voltage not directly reported
Heating Element	Virtual coil + load (no specific material)	Real steel pieces (15g–45g)
Measurement Tools	MATLAB Simulink plots and scope blocks	IR thermometer for temperature, clamp ammeter for current, regulated power supply for voltage
Results Type	Theoretical (current and voltage vs time)	Empirical (temperature vs time for steel samples)
Application Behavior	Idealized model assuming resonance and perfect switching	Real-world inefficiencies present (heat loss, coil losses, imperfect resonance)

Notable Observations:

Voltage and Current: The simulation assumed significantly higher operating voltages (up to 75V) resulting in higher current (>50A), whereas the real system operated at 12V with currents peaking below 10A.

Thermal Output: Chapter 4 shows real heating curves with temperature rise in °C over 60 seconds for different steel masses. Simulations didn't model temperature, only voltage/current.

Circuit Behavior: Both use ZVS principles with LC resonance, but actual behavior in the lab (Chapter 4) is influenced by coil design, load type, and ambient heat dissipation.

Real vs Ideal: Simulations show smoother, ideal current and voltage curves, while the experiment exhibits varying heating efficiency depending on the steel sample.

IV.6 Discussion of Challenges and Solutions :

In the process of conducting real-world tests and analyzing the induction heating system, several technical and practical challenges were encountered. These challenges affected measurement accuracy, heating efficiency, and system stability.

This section outlines the key issues faced and the solutions implemented to overcome them.

IV.6 -1. Limited Heating Power Due to Low Voltage Supply :

- **Challenge:**

The system was powered by a 12V DC supply, which limited the total power output and consequently the heating rate of larger or denser steel samples.

- **Impact:**

- Slower heating for steel samples above 30g.
- Maximum temperature achievable within 60 seconds was limited (420°C for the largest sample).
- Lower current draw than expected compared to simulated values (max ~9.8A vs. 50A in simulation).

- **Solution:**

- The coil was optimized for fewer turns (11 turns) to improve current flow and concentrate the magnetic field.
- Testing was limited to small steel parts (under 50g), which allowed efficient heating within the constraints of the power supply.
- For future improvements, using a 24V or 36V supply is recommended to increase heating speed and max temperature.

IV.6 -2. Inconsistent Heating Due to Coil and Load Positioning :

- **Challenge:**

Precise alignment of the steel object within the induction coil was critical. Small changes in position caused variations in heating rate and surface temperature.

- **Impact:**

- Some tests required repetition due to misalignment.
- Inconsistent readings in early trials, especially with non-centered or tilted parts.

- **Solution:**

➢ A non-metallic stand was used to ensure consistent placement of steel samples at the center of the coil.

➢ Markings were added to position each object uniformly.

➢ For improved uniformity, future designs can include a guided placement fixture.

IV.6 -3. Measurement Accuracy and Thermal Lag :

- **Challenge:**

Temperature measurements relied on a handheld IR thermometer, which was sensitive to angle, distance, and surface reflectivity of the heated object.

- **Impact:**

➢ Small measurement delays or inaccurate readings during fast temperature changes.

➢ Reflective surfaces (e.g., polished steel) skewed temperature readings.

- **Solution:**

➢ Distance and angle were standardized for all measurements (~5–10 cm at 90°).

➢ Surfaces were darkened (e.g., with black marker or oxidation) to improve emissivity and reduce reflection error.

➢ Repeated measurements were averaged for each time point.

IV.6 -4. Component Heating and Efficiency Loss :

- **Challenge:**

Prolonged operation of the ZVS circuit led to heating of MOSFETs and capacitors, which could impact efficiency and potentially damage components.

- **Impact:**

- Slight drop in voltage after 40–50 seconds.
- Risk of thermal shutdown or failure during extended testing.

- **Solution:**

- A heat sink and active cooling (small fan) were added to the MOSFETs (IRFP260N).
- Testing intervals were limited to 60 seconds to avoid overheating.
- Capacitors were selected with a high voltage and temperature rating (275V AC film types).

IV.6 -5. Discrepancies Between Simulation and Real Results :

- **Challenge:**

The simulated system (Chapter 3) used higher voltages and ideal circuit parameters, leading to discrepancies in current, heating rate, and system behavior.

- **Impact:**

Simulated results showed faster energy transfer and higher power levels.

- **Solution:**

- Experimental results were analyzed independently, with clear mention of real input limits.
- Chapter 4 explicitly contrasts simulated and actual performance for clarity.
- Future simulations should model realistic supply constraints and thermal loads.

IV.7 Conclusion :

Despite the challenges, the experimental setup successfully demonstrated the feasibility of magnetic induction heating using a low-cost, 12V ZVS circuit. The real measurements provided valuable insights into practical limitations, efficiency factors, and heating behavior of different steel geometries.

These lessons can inform future designs with higher voltage supplies, improved measurement systems, and enhanced thermal management.

A 12 V ZVS-based induction heater can successfully raise small steel parts to high temperatures (400+ °C) in under 60 seconds.

This makes the system viable for compact heating tasks such as brazing, soft forging, and thermal testing.

For longer durations or heavier loads, improved cooling and possibly higher voltage (24 V) are recommended.

General conclusion

General conclusion

We attempted to explore induction heating utilizing the REALIZATION OF MAGNETIC INDUCTION HEATING . Many efforts have been made to design and optimize electromagnetic induction (heating) systems because of their extensive application in industry.

In this work, we used mathematical connections to construct a study of thermal and electromagnetic processes in induction heating equipment. We applied the characteristic partial equations of Maxwell's equations, which are the foundation of electromagnetism, to the thermal and magnetic physical phenomena that needed to be addressed.

The completion of this project has demonstrated the practicality and efficiency of induction heating systems, specifically in low-voltage applications using a ZVS inverter topology. Through careful theoretical study, system architecture planning, component selection, and empirical validation, a robust prototype was developed capable of delivering effective thermal energy to metallic loads.

From a theoretical standpoint, the project applied foundational electromagnetic principles—such as Faraday’s and Lenz’s laws, the Joule effect, and skin effect—to explain the mechanism by which alternating magnetic fields induce eddy currents and localized heating within conductive materials. These principles were validated both through mathematical modeling and simulation using MATLAB/Simulink.

The design and engineering phase involved the construction of a power supply, rectification unit, ZVS inverter circuit, and a resonant LC tank. Special attention was given to achieving resonant frequency matching, minimizing energy loss, and ensuring system safety through thermal control and cooling solutions. The coil design, number of turns, and wire gauge were optimized for effective magnetic field generation and current flow.

In the simulation phase, results indicated successful resonance at calculated frequencies, with high current amplitudes and sinusoidal voltage waveforms consistent with efficient energy transfer. These were further confirmed by real-world measurements and experimental tests on steel workpieces of varying shapes and masses. The temperature-time curves obtained through thermocouples and IR cameras revealed rapid and repeatable heating responses, with performance differences based on geometry and mass of the objects.

From a practical perspective, the system exhibited strong performance in heating steel objects (bolts, nuts, washers, etc.) with a power input limited to 12V, showcasing the viability of compact, low-cost induction heating systems for small-scale or portable applications. The use of MOSFETs, capacitors, and robust thermal management ensured the longevity and safety of the setup.

Challenges, such as circuit tuning, component overheating, and limited frequency range, were addressed through iterative refinement and simulation-based troubleshooting. Recommendations include enhancing power levels, adding digital PID control for temperature regulation, and integrating wireless monitoring features for industrial applications.

In conclusion, the project not only met its objective of designing and realizing a functioning induction heating prototype but also contributed valuable insights into the behavior of electromagnetic heating systems. It serves as a foundation for future research into energy-efficient, digitally controlled, and scalable induction heating solutions for manufacturing, materials processing, and consumer electronics.

Annexes

Annexe : Chapitre 3

1) Partie Simulink Matlab :

a) Scheme Matlab Simulink :

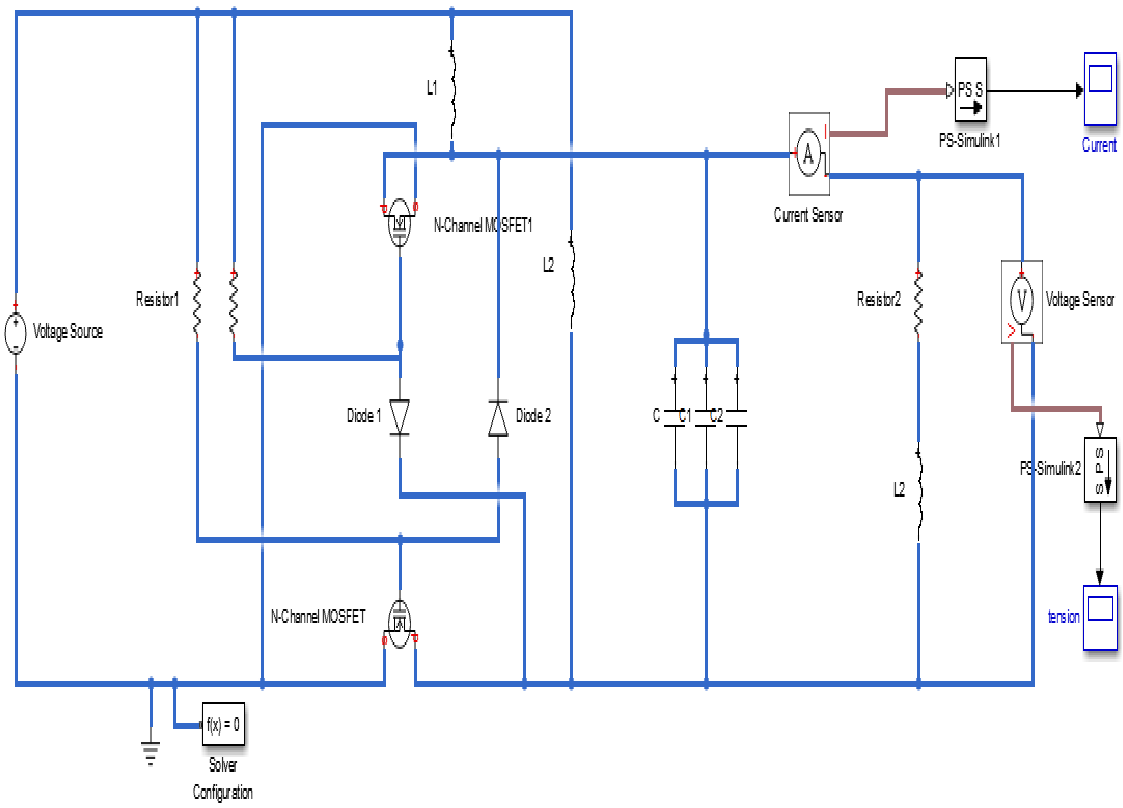
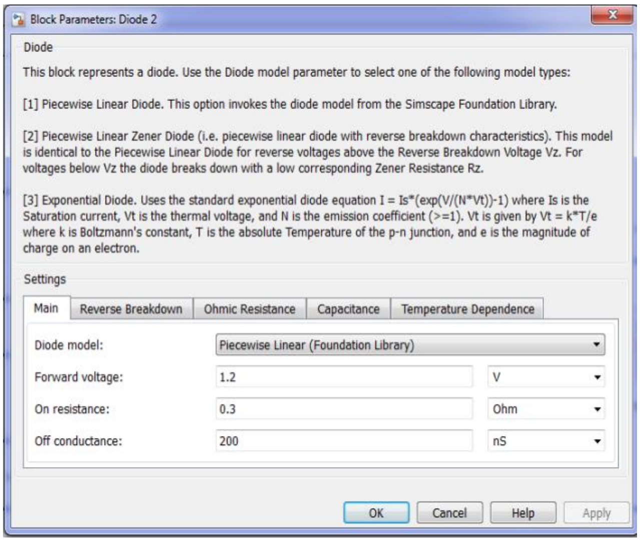
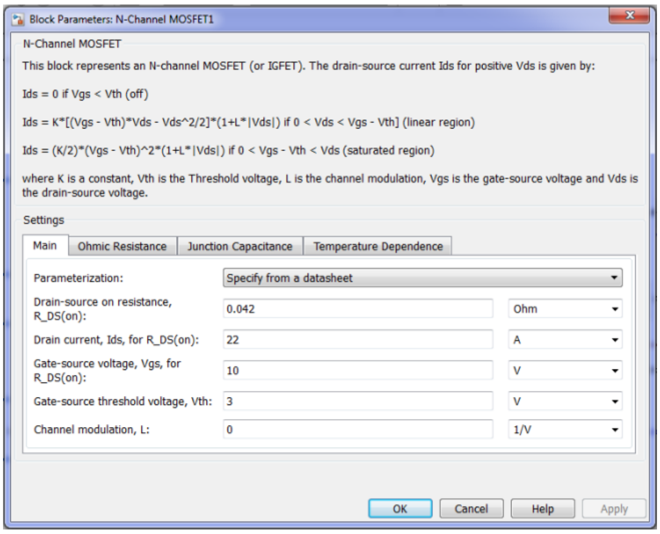
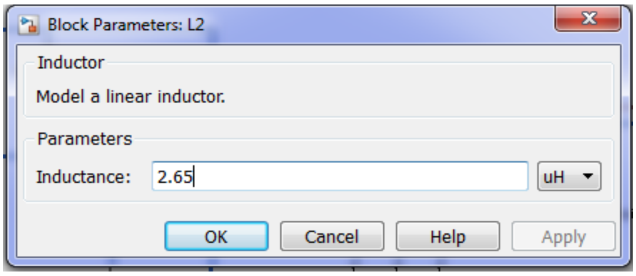


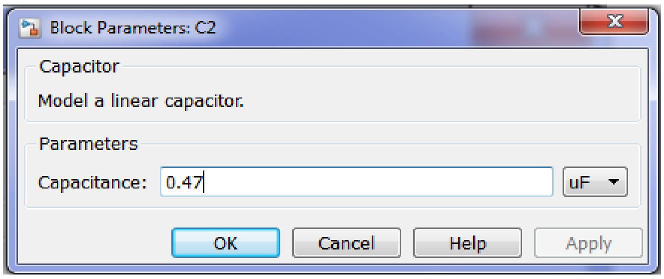
Figure .1: Block diagram under

b) **Simulation parameters:**









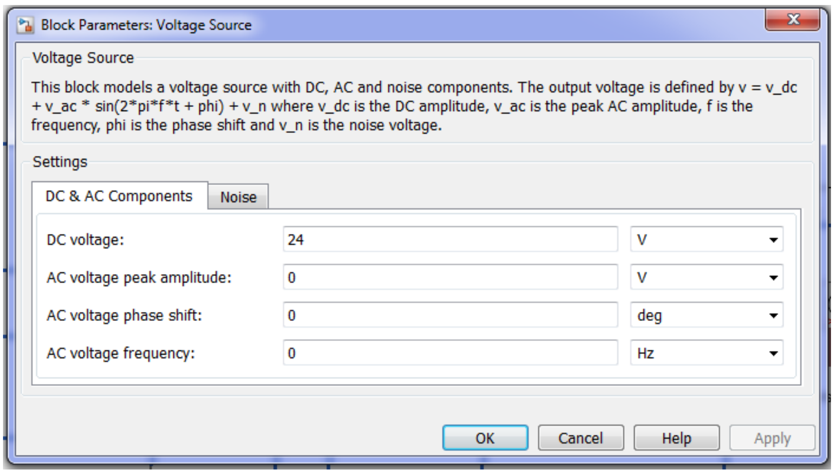


Figure .2: Simulation parameters under Matlab Simulink.

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