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Entitled

Design and Implementation of an Induction Heater

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Before the Jury composed of:

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Dedication

My gratitude and appreciation go to my Lord who enlightens my path and supports me. Thank you for the light in my eyes, the soundness of my hearing, and the clarity of my mind.

How can I forget, as I dedicate myself completely, even my name, to my mother? And I offer all my efforts as a tribute to my father.

To all my brothers and sisters who have had a profound impact in overcoming numerous obstacles and difficulties.

I thank everyone who supported and assisted me, and I dedicate this work to all the minds that have been armed with knowledge.

Issam

Dedication

I dedicate this humble work to the one who raised me with prayers and supplications, to the dearest person in existence, my beloved mother, may Allah prolong her life.

To the one who encouraged me in pursuit of knowledge and instilled hope in me all these years, my dear father, may Allah protect him.

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Iyad

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Chapter I

Abstract

Induction heating is an electromagnetic technique used as a thermal source for the treatment and transformation of metals, cooking, assembly of conductive parts, and more. Its efficiency and effectiveness make it highly sought after in various industrial applications.

The aim of this project is to conduct a comprehensive study on the induction heating system, covering multiple aspects including magnetic, thermal, and power electronics. In this context, a model has been built, studied, and simulated, taking into account all the parameters governing induction heating. Experimental tests have been conducted, and the obtained results have validated the adopted design approach.

Keywords: Induction heating, Eddy current, Resonant circuit, Design, Inductor, Induction power generator.

Résumé

Le chauffage par induction est une technique électromagnétique utilisée comme source thermique pour le traitement et la transformation des métaux, la cuisson, l'assemblage des pièces conductrices, etc. Sa performance et son efficacité en font une méthode très demandée dans plusieurs applications industrielles.

L'objectif de ce projet est d'effectuer une étude approfondie sur le système de chauffage par induction, en couvrant plusieurs aspects tels que le champ magnétique, la thermique et l'électronique de puissance. Dans ce contexte, une maquette a été réalisée, étudiée et simulée en prenant en compte tous les paramètres qui régissent le chauffage par induction. Des essais expérimentaux ont été réalisés, et les résultats obtenus nous ont permis de valider l'approche de conception adoptée.

Mots-clés : Chauffage par induction, Courant de Foucault, Circuit résonant, Conception, Bobine, Générateur de puissance par induction.

ملخص

التسخين بالتوالد هو تقنية كهرومغناطيسية تستخدم كمصدر حراري لمعالجة وتحويل المعادن، الطهي، وتجميع الأجزاء الموصلة، وغيرها. يتميز بكفاءته وفاعليته مما يجعله مطلوبًا جدًا في العديد من التطبيقات الصناعية.

هدف هذا المشروع هو إجراء دراسة شاملة عن نظام التسخين بالتوالد، وذلك فيما يتعلق بالجوانب المغناطيسية والحرارية والإلكترونية للطاقة. تم تنفيذ نموذج عمل ودراسة ومحاكاة النموذج باعتبار جميع المعاملات التي تحكم نظام التسخين بالتوالد. تم إجراء تجارب عملية، وقد ساهمت النتائج المحصلة في التأكد من الأسلوب المتبع في التصميم.

كلمات مفتاحية: التسخين بالتوالد، التيار الدوامي، الدائرة المتذبذبة، التصميم، الملف الكهرومغناطيسي، مولد الطاقة بالتوالد

General Introduction

Induction heating, also known as electromagnetic heating, is a widely used method in industry for heating and melting various materials. It offers numerous advantages compared to other heating methods, such as high energy efficiency, rapid heating, precise temperature control, and cleanliness. This technology finds extensive applications in areas like metal melting, surface hardening, heat treatment, and induction brazing.

The aim of this research is to provide a comprehensive overview of the induction heating process, focusing on the fundamental principles, system components, and applications. The first chapter presents a general introduction to the preheating process by defining the concepts of heating and melting, and examining the energy sources utilized in smelting, heating, and grading furnaces.

Various types of furnaces, including solid fuel, liquid and gas fuel, and electric furnaces, are discussed in detail. The applications and environmental impacts of induction heating are also highlighted.

Chapter II focuses on the basics of induction heating. It begins with an introduction to the historical background of induction heating, followed by an explanation of the principles of induction heating/melting. Different geometries and types of inductors used in induction heating, such as multi-turn helical inductors, single-turn inductors, multi-position helical inductors, tunnel inductors, curved channel inductors, pancake inductors, shared helical inductors, and special forms, are discussed. The energy losses due to Joule effect and hysteresis, as well as the electrical model of the inductor-workpiece system, are explained in detail.

Chapter III addresses induction heating converters. It provides an overview of power semiconductors used in induction heating systems and presents the complete block diagram of an induction heating system. The rectification system and the modeling of the chopper, particularly the series chopper or buck converter, are discussed. The types of resonance converters, energy balance, advantages of Voltage-Fed Series Resonant Inverters (VFSRI), and the modeling of the voltage inverter are also covered. The resonant frequency, quality factor, power in the workpiece, and commutation analysis considering parasitic capacitances and dead-time are explored.

In conclusion, this research provides a solid foundation for understanding the principles of induction heating, system components, and associated technical aspects. It will be valuable for researchers, engineers, and industry professionals interested in the applications of induction heating and melting. [1]

Chapter I:

Generalities of preheating

I.1. Introduction

In this first chapter, an introduction to preheating is presented. The concepts of heating and melting are defined, and the energy sources used in smelting, heating, and grading furnaces are discussed. These sources include solid fuel furnaces, liquid and gas fuel furnaces (such as flame furnaces and crucible furnaces), and electric furnaces (including electric resistance furnaces, electric arc furnaces, and induction furnaces). The applications and environmental impacts of preheating are also explored.

The focus then shifts to induction heating and melting, providing a definition of the process and discussing the different types of induction furnaces, including core type or low-frequency induction furnaces and coreless type or high-frequency induction furnaces. The advantages of induction heating and melting are highlighted, such as high efficiency, precise control, speed, and localized heating.

Lastly, a comparison is made between induction heating and gas coal heating and resistance heating, examining differences in efficiency, environmental impact, and suitability for various applications.

This introductory chapter lays the foundation for the subsequent chapters, providing knowledge and understanding of the general principles and applications of preheating.

I.2. Definition of heating

Heat treatment is the process of heating and cooling minerals to change their microstructure and to bring out the physical and mechanical properties that make the metal more desirable. Metals are heated to temperatures, and the rate of cooling after heat treatment can dramatically change the properties of the metal. [2]

I.3. Definition of melting

change of a solid into a liquid when heat is applied. In a pure crystalline solid, this process occurs at a fixed temperature called the melting point; an impure solid generally melts over a range of temperatures below the melting point of the principal component. [3]

I.4. Energy sources used in smelting/heating and grading furnaces

The methods of heating can be expressed in different ways, but here some common methods of hating metals [4]

I.4.1. Solid fuel furnaces

The most important of which are cupola furnace and reverberatory furnace flame reflector. The domed furnace (**Figure. I. 1**) consists of a long steel cylinder standing vertically on solid bases lined with thermal bricks, and at its upper end, when connected to the chimney, the filling hole, from which the furnace is supplied with a metal charge consisting of iron ore, coke and smelting aids (slag problems). With the heat from the combustion of coal at the air blowing belt, the iron is melted and collected at the bottom of the furnace (basin), from which it is emptied into the crucibles of pouring, and this furnace is for melting iron ore and converting it into cast iron and is not used for smelting other metals.

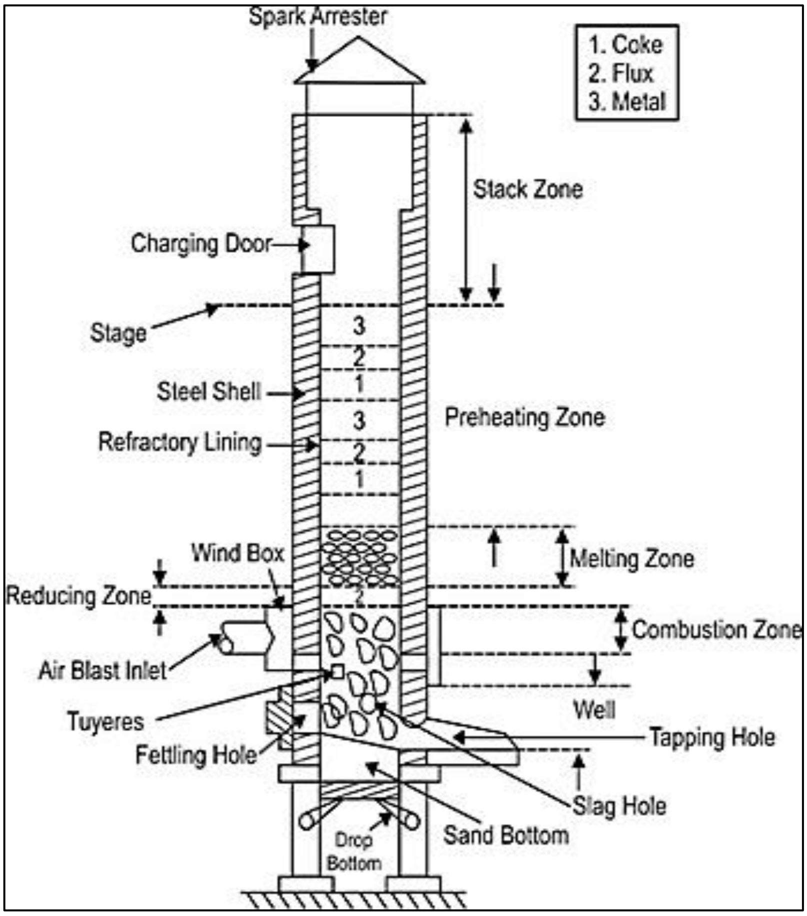

Figure. I. 1 : the domed furnace

The flame reflector furnace (**Figure. I. 2**) consists of two adjacent chambers of convection bricks, the first is the burner or stove where the coal is burned, and the second is the furnace basin, combined by a common roof whose shape helps direct the flame coming from the stove towards the surface of the basin to melt the metal charge, and the combustion gases exit to the chimney on the other side of the basin. This furnace is used to melt iron and other metals, but it has become rare and of little use. [4]

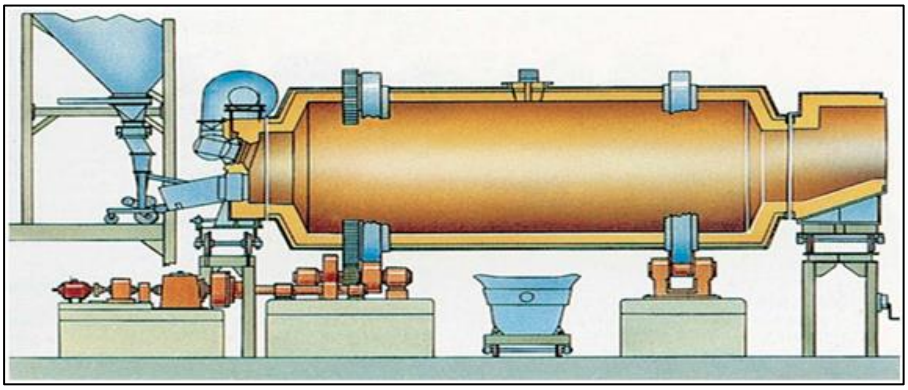

Figure. I. 2 : the flame reflector furnace

I.4.2. Liquid and gas fuel furnaces

the most important of which are the flame furnace and crucible furnace:

- **The flame furnaces**

(**Figure. I. 3**) consists of a long basin of convection bricks and compacted refractory soil at one end of which is the flame and burner channel, and the chimney at the other end. The burner mixes the gas with the air needed for combustion and ignites it within the flame channel to head towards the charge placed in the furnace basin, and the gases exit from the other side into the chimney. In the case of using liquid fuel (diesel or heavy oil), the burner is more complex as it atomizes or vaporizes the fuel before mixing it with the necessary air.

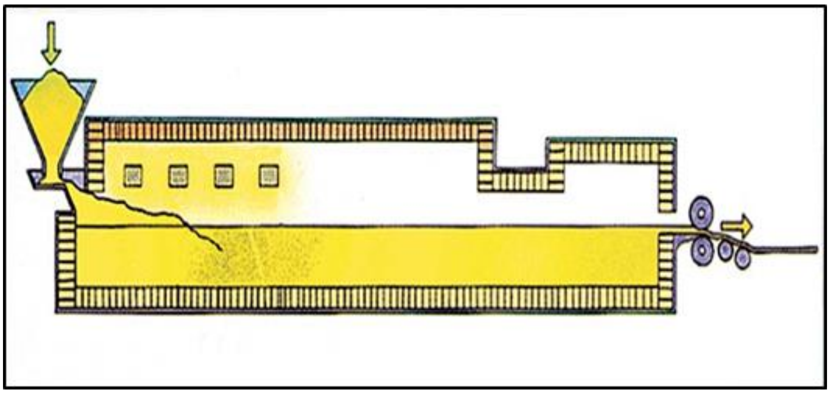

Figure. I. 3 : the flame furnace

- **As for the crucible furnace**

It is a hollow steel cylinder and vertical open at the top and lined from the inside with thermal bricks, on one side of the burning and on the opposite side the opening leading to the chime.

The pieces of metal prepared for smelting are placed in a crucible inside the furnace, and after closing the furnace opening, the flame is shed on the crucible from one side and rotates around it in a vortex before the combustion gases leave for the chime, and then the melting is done indirectly, so the metal does not come into contact with the combustion products, but the crucible plays the role of mediator in transferring heat to the charge. These furnaces are used in workshops and factories with limited productivity or in the smelting of metals affected by combustion gases. The crucible is installed in the furnace liner in some types of furnaces (**Figure. I. 4**) and the entire furnace is of a forward-tilting type to discharge the molten metal.

The furnaces of this group are suitable for melting all types of metals, but with a difference in the quality of the thermal lining, the quality of the crucible and the thermal capacity of the furnace, to suit the characteristics of the metal that is used to melt it. Crucible furnaces are also used for smelting salt mixtures used in heat treatment of steel.

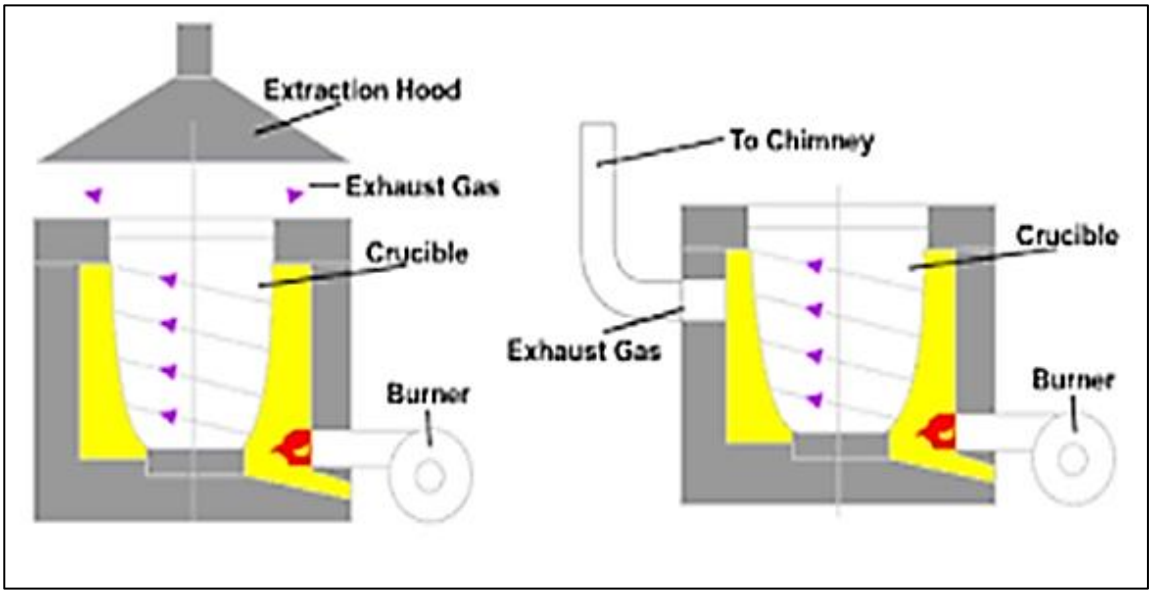

Figure. I. 4 : the crucible furnace

I.4.3. Electric Furnaces

Electric energy is used to heat and melt all metals in one of three ways: heating by resistance, heating by electric arc, and heating by induction.

- **Electric resistance furnaces**

The melting in these furnaces can be direct or indirect, in direct heating the furnace is in the form of a vacuum steel cylinder lined with refractory materials (**Figure. I. 5**), placed horizontally on a Bearings, and along its axis a solid column of graphite connected from its ends to the electric current, to form the electrical resistance that with its glow leads to heating the metal charge placed inside the furnace and melting it. The cylinder rotates around its axis to take advantage of heat distribution over its entire inner surface. As for indirect heating, it takes place in crucible furnaces similar to those that use liquid or gaseous fuel, but they do not contain a burner and a chiming hole, but the crucible and the inner lining of the furnace are separated by a set of electrical resistors fed by the necessary thermal energy, and these furnaces are often of the type with a fixed crucible and capable (i.e. furnaces) to rotate or tilt forward to empty the molten metal, except for the small ones, which have a moving crucible.

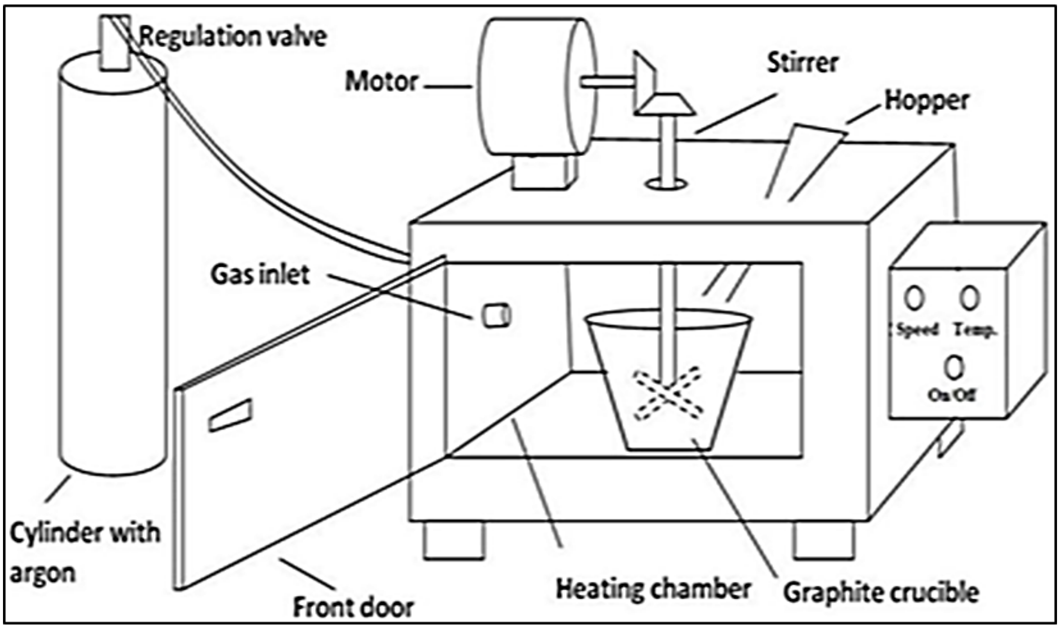

Figure. I. 5 : electric resistance furnaces

- **Electric arc furnaces**

An electric arc furnace consists of a cylindrical body, a concave base, and a convex roof that can be lifted and displaced (**Figure. I. 6**), from which hangs from the furnace roof three electrodes (rarely electrodes) of solid graphite, movable up and down. After the charge is placed in the furnace, the electric current is connected to the electrodes and moved at a distance from the surface of the metal charge, allowing the current to be vacuumed and forming an electric arc between both the electrodes and the metal charge. The heat from the electric arc and the flow of current in the metal charge causes it to melt. The furnace rests on a Bearings so that it can be tilted forward to empty the molten metal, while it is fed with hard metal either from above after displacing the roof or from a side opening.

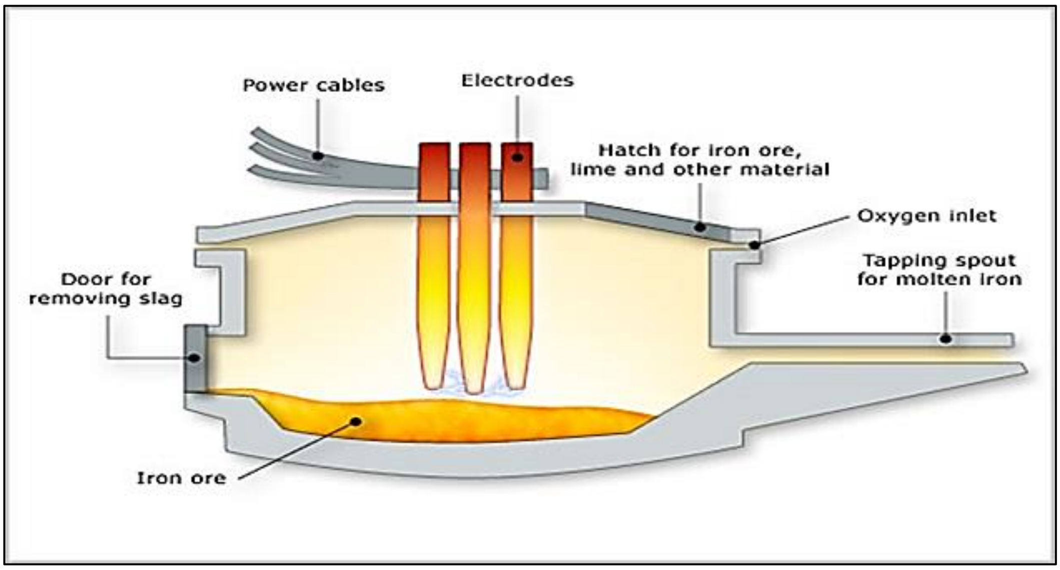

Figure. I. 6 : electric arc furnaces

- **Induction furnaces**

The induction furnace consists of the following main parts: a cylindrical crucible made of pressurized refractory materials (**Figure. I. 7**), cast iron or steel (for smelting some non-ferrous metals), equipped at its front edge with a casting channel, wrapping around the crucible and an electric coil made of copper tubes in which a water stream passes to cool them during work. The coil reaches a high-frequency electric current, so the furnace becomes an electrical transformer whose primary coil is the coil, and its secondary coil is the metal charge inside the crucible or crucible itself if it is iron or steel, so the secondary coil induces a high-intensity electric current that heats and melts the charge. The furnace is often carried in the middle on two side bases so that it can be rotated forward to discharge after the smelting is over.

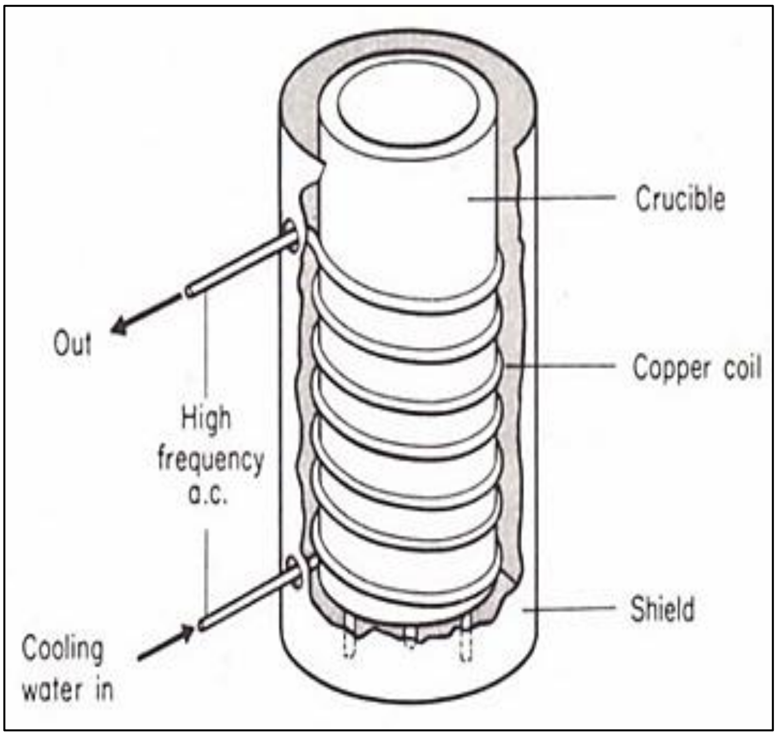

Figure. I. 7 : induction furnaces

I.5. Applications and environmental impacts

The mining industries, which grew rapidly in the twentieth century, are among the most harmful to the environment for two reasons: the first is the depletion of natural resources such as ores, fuels and others, and the second is the harmful gases they release into the atmosphere loaded with solid plankton, which are no less harmful, and the liquid or solid waste they leave that disintegrate and seep into groundwater.

Smelting is part of mining operations, and the rest of the operations are involved in harming the environment, especially when coal or liquid fuels are used for heating. However, since environmental protection began in the second half of the last century, many countries have been committing various industries to measures to reduce pollution. So many foundries are switching from traditional smelting using coal or oil for heating, to using electric furnaces, and many combustion gases and industrial wastewater are being treated before being released into the outer environment. Attention has increased to solid waste and its remitting to mitigate its environmental damage on the one hand, and to save on the consumption of natural resources on the other. [4]

I.6. Induction Heating/melting

Induction heating is a method of heating using electromagnetic induction. It involves the use of an alternating current passed through a coil to create a changing magnetic field. When a conductive material is placed within this field, it experiences induced electrical currents that generate heat. This process allows for efficient and precise heating in various industrial applications.

I.6.1. Definition

Induction Heating is a contactless electric heating process where electrically conductive materials are heated by the principle of electromagnetic induction. Here heat is generated within the conductive material without making direct contact with the source.

We all are aware of the fact that earlier, the heating process that was mostly in use needs direct contact between the metal to be heated and the flame. More specifically, we can say that non-electric heating requires a direct placing of metal over the flame. However, induction heating allows inducing heat within the metal by the circulation of electric current. [5]

I.6.2. Types of Induction Furnace

Induction furnaces are basically two types, they are: [6]

- Core type or low-frequency induction furnace
- Coreless type or high-frequency induction furnace

- **Core Type or Low Frequency Induction Furnace**

This furnace consists of a circular hearth in the form of a trough, which contains the charge to be melted in the form of an annular ring. The iron core is large in diameter and is magnetically interlinked with an electrical winding energized by an ac source as shown below. The furnace is therefore essentially a transformer in which the charge to be heated forms a single turn short-circuited secondary and is magnetically coupled to primary by an iron core. The charge is melted due to the heavy current induced in it. When there is no molten metal, no current will flow in the secondary. Thus, to start the furnace, the molten metal is to be poured into the hearth. The core type induction furnaces are again classified into two types, direct and indirect core type induction furnaces. In a direct core type induction furnace, the charge to be heated will form the single-turn secondary circuit as shown above. Whereas in an indirect core type induction furnace, there will be a heating element that forms secondary, the heat produced in the heating element is transmitted to the charge by radiation. (**Figure. I. 8**) [6]

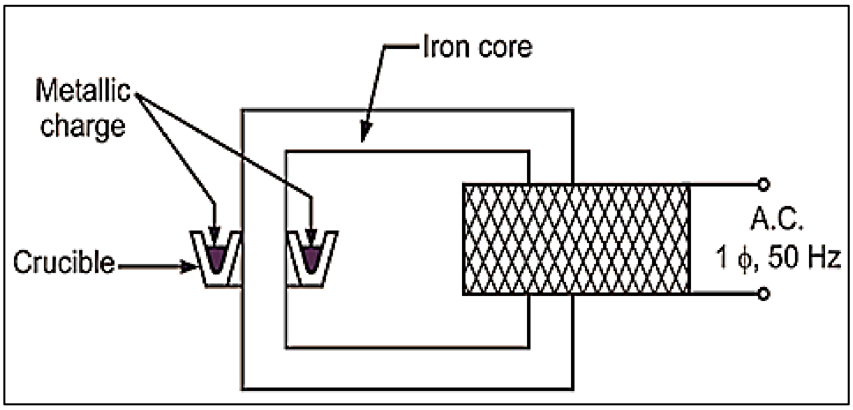

Figure. I. 8 : low frequency induction furnace

- **Coreless Type or High Frequency Induction Furnace**

In a core type induction furnace, there is an iron core through which primary and secondary are magnetically coupled. But in a coreless induction furnace, there is no core and thus heating of material will be due to eddy currents flowing through it as shown below. The furnace consists of a refractory or ceramic crucible in a cylinder shape. The crucible is surrounded by a coil which acts as the primary. When this primary is connected to an ac supply, it induces an eddy current in the charge to be heated. The eddy current induced will develop heat in the charge and also an additional stirring action due to electromagnetic forces is produced in the charge.

Due to the absence of a core in this furnace, flux density in the furnace is low. Thus, the supply to the primary should be of high frequency in order to compensate for low flux density, hence this furnace is also called a high-frequency induction furnace. (**Figure. I. 9**)[5]

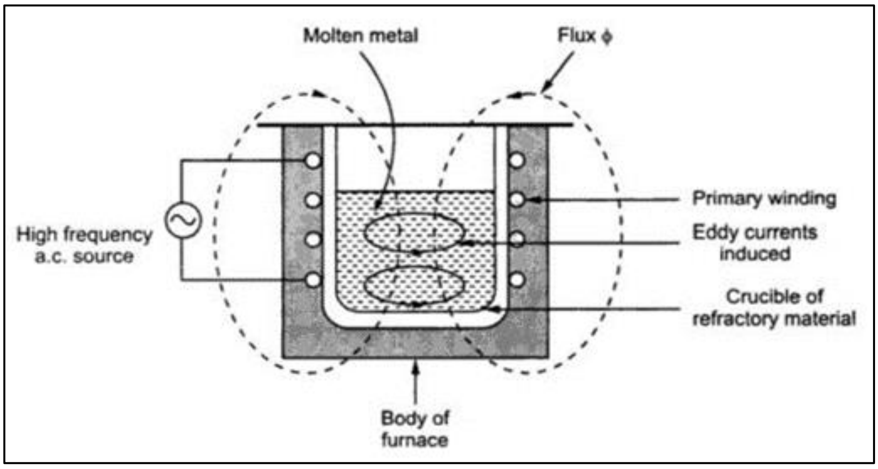

Figure. I. 9 : High frequency induction furnace

I.6.3. Advantages of Induction Heating/melting

We can find many advantages of induction heating, and here are some of them: [6] [7]

- The various advantages of induction heating are
- It is suitable for periodic operations
- The heating of material is carried out without making any direct contact with the power supply.
- There is no noise, dust, dirt, or smoke in its operation, thus the working conditions are pleasant.
- Flexible temperature control and heat transfer can be very closely monitored.
- In very less time it reaches the melting point.
- It has very high constant and precise heating.
- For the production of high-grade alloys, induction heating is most suitable.
- Technological advancements made the induction heating process a useful tool in the industry of heat treatment plants.
- This method is more precise for surface hardening of metals and nonferrous metals.
- Automatic temperature control can be done with the help of timers and feedback systems.
- In the process of induction heating, any by-products are not realized.
- For induction heating, no such skilled labors are required, thus the operating costs are also reduced.

I.6.4. Differential Characteristics of Induction Heating Applications for Each Enabling Technology

Table. I. 1 : Differential Characteristics of Induction Heating Applications for Each Enabling Technology [7]

		Enabling Technology		
		Modulation and Control Algorithms	**Magnetic Components**	**Power Electronics**
Application	**Industrial**	▪ High power. ▪ Improved reliability ▪ Assembly-line read. ▪ Low-high operating frequency	▪ Multi-zone control algorithm. ▪ Improved interface and communications. ▪ Variable load and power ranges. ▪ Multi-load management. ▪ Temperature control.	▪ High efficiency. ▪ Variable shape. ▪ Optimized heat distribution.
	Domestic	▪ Low cost. ▪ High efficiency. ▪ Limited cooling capability. ▪ Medium operating frequency.	▪ Power factor and harmonics control. ▪ Variable load and power ranges. ▪ Need to avoid acoustic noise. ▪ Multi-load management. ▪ Temperature control.	▪ High efficiency. ▪ Heat non-ferromagnetic materials. ▪ Flexible cooking surfaces.
	Medical	▪ Low power. ▪ High operating frequency. ▪ High quality factor resonant tank.	▪ Accurate power and temperature control. ▪ Frequency selection.	▪ Local heating. ▪ Controlled magnetic field interactions. ▪ Ferromagnetic fluids.

I.7. Comparison between induction heating and resistance gas coal heating

Table. I. 2: Comparison between induction heating and resistance gas coal heating [8]

description	Induction	Coal ignition heating	Gas ignition heating	Resistance heating
Heating efficiency	98%	30 to 65%	80%	less than 80%
Polluting emissions	• without noise • without dust, • without exhaust gases • without leftovers	• Coal ash • Smoke • Carbon dioxide • Sulfur dioxide	• carbon dioxide • Sulfur dioxide	• Without
Contamination	• without pollution	• pollution	• pollution	• pollution
Water purification	• Depends on fluid quality	• Required	• Required	• Required
Heating stability	• Constant	• Capacity decreases by 8% per annum	• Capacity decreases by 8% per annum	• Capacity decreases by more than 20% per year (high power consumption)
Security	• Separation of water from electricity • Without electrical leakage • Without radiation	• Risk of carbon monoxide poisoning	• Risk of poisoning and exposure to carbon monoxide	• Risk of electrical leakage • Electric shock or fire
Durability	• Thanks to the mold design of the heating unit, the service life is 30 years	• 5 years	• From 5 to 8 years	• From half to one year

I.8. Conclusion

In conclusion, after highlighting the different types of solid metal heating furnaces and comparing them with induction heating furnaces, we can conclude that induction heating furnaces are an excellent choice due to their numerous advantages and wide range of applications. These furnaces are characterized by high efficiency and energy savings, rapid heating, and precise temperature control.

In summary, induction heating furnaces represent an advanced and efficient technology that combines high performance with energy efficiency, making them a preferred choice in many different applications.

Chapter II:

Induction heating basics

II.1. Introduction

In this chapter, the fundamental concepts related to induction heating are introduced.

First and foremost, the stages of the development of induction heating and its working principle are presented. Following that, an overview of the structure and types of the file is provided

Lastly, the main ideas in the chapter are summarized.

II.2. Background of induction heating

The principles of induction heating are based on the laws formulated by the great pioneers of electromagnetism.

Firstly, Michael Faraday (1791-1867) must be mentioned, in 1831 he performed an inverse experiment compared to the experiments of Oersted, who discovered that the electric current creates the magnetic field that causes deviation of the magnetic needle. Faraday found that when the magnet approached a close loop of the electric circuit, a pulse of electric current was induced in the circuit. Removing the magnet caused again the current pulse. After multiple experiments, Faraday formulated a principle of electromagnetic induction which states that any variation of the magnetic flux coupled to a contour generates electromotive force in the contour which is proportional to a speed of the flux variation in time. Soon after H. Lenz showed that the induced current has always a direction that obstructs the magnetic flux variation. With this important addition the formula of electromagnetic induction became one of the cornerstones of the electromagnetism.

Several very important studies of magnetic and electric phenomena followed. In the course of his studies of the heat generated in an electric circuit, James Prescott Joule (1818-1889) formulated the law of electric heating in 1840, known as Joules law. It states that the amount of heat produced in a conductor by an electric current per each second is proportional to the resistance of the conductor and to the square of the current. Joule, also studied conversion of mechanical energy in thermal energy and found the numerical relation between these two types of energy, i.e., the mechanical equivalent of heat.

A crucial role in the theory of electromagnetism belongs to James Clerk Maxwell (1831-1879), Based on findings of Oersted, Faraday, Ohm, Joule, Ampere in the electric and magnetic studies and applying to their description the mathematical apparatus developed by Gauss, Green and other scientists, he created his ingenious theory of electromagnetism. This theory combined the electric and magnetic phenomena, explained all facts known at that time and predicted new features such as the electro-magnetic nature of light and the electromagnetic waves that must propagate in space with the speed of light. Existence of these waves was confirmed experimentally by Heinrich Hertz in 1887, Maxwell derived equations that describe all phenomena of electromagnetism.

Discovery of the dynamoelectric principle by Werner Siemens (1816-1892) in 1866 and the invention and development of the first technically usable direct current dynamo-machine in 1867 created a basis for power generation and started the era of electrical engineering. W. Siemens, coined the German term Electrotechnics, which was originally referred to a field of the Applied Theory of Electricity. Sometime later Nicola Tesla (1856-1943), discovered the rotating magnetic field, the basis of alternating current motors. In the 1880s, he studied and introduced polyphase electrical systems that became the basis of the power system with electric lines, alternating current motors and transformers. He also built one of the first “medium frequency” motor generators which he used for demonstration of a possibility of energy transfer without contact by the magnetic.

Charles P. Steinmetz (1865-1923), strongly contributed to the theory and practice of electrical engineering including methods of calculation and design of transformers and rotating machines. He introduced complex quantities in the practice of calculation of the electric and magnetic systems. Studying penetration of an electromagnetic field into materials, he coined the term “electromagnetic penetration depth” playing a central role in calculation of induction devices.

We can see that at the end of the nineteenth century all the basic knowledge about electromagnetic induction, heat generation by electric currents, AC power generation as well as important calculation basis was already available to the scientific and engineering community around the world. [9]

II.3. Principle of Induction Heating/Melting

Before discussing the construction and operation of induction heating, let us see about the principle of induction heating. The principle of operation of induction heating is based on Faraday’s law of electromagnetic induction and on the concept of Joule or resistance or ohmic heating. The below (**Figure. II. 1**) represents the principle of induction heating.

Induction heater units incorporate high frequency generators for non-contact heating of metal using electromagnetic induction.

When AC is applied to a coil surrounding the work (metal), a magnetic field is generated by the current flowing in the coil, and induced loss (hysteresis loss) is generated causing a heat.

At the same time, in the magnetic field which alternates with the AC, a spiral current (eddy current) is generated by the electromagnetic induction. This eddy current generates Joule heating, and a heat loss of the electromagnetic energy (eddy-current loss) will be caused

High frequency induction heating equipment performs heating by utilizing the two-heating principle, namely hysteresis loss and eddy-current loss [10]

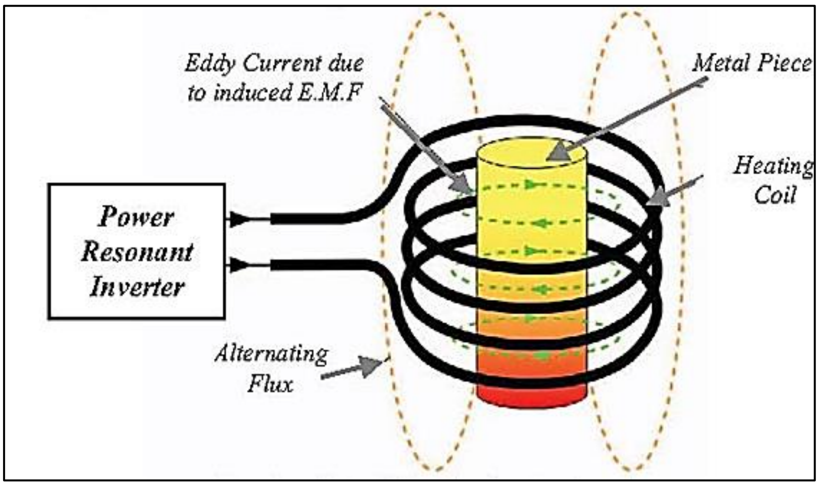

Figure. II. 1 : Principle of Induction Heating

II.4. Coil length

In continuous wire heating processes, the length of the inductor coil determines the amount of time the wire is heated. A shorter coil with fewer turns results in lower resistance, but requires more current and produces greater losses in the inductor. Coil length is chosen based on converter limits and maximum current allowed in the coil. Cooling systems for heating inductors can become oversized if current is very high. For thick pieces, heating time is determined by heat propagation time to the center, and if the surface is heated too quickly, non-homogeneous heating and mechanical stress can occur. To prevent this, maximum power density and temperature difference between surface and center are imposed. Analytical methods and tables can be used for simple workpiece shapes, but numerical computation is necessary for precise analysis. [11]

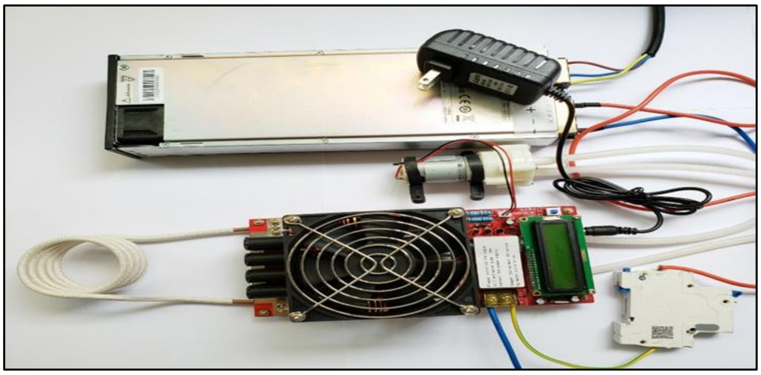

Figure. II. 2 : High-frequency industrial heating module for metal smelting

II.5. Geometries and types of Inductors

Because each induction heating application requires a unique heating profile, inductor shapes and sizes can vary widely. The geometry of the inductor depends not only on the desired heating profile but also on the type of generator used. [12]

The induction coil is a conductor made of water-cooled copper tubing. Inductors can take various forms, such as:

II.5.1. Multi-turn helical inductor

Spiral inductors (solenoids) are the most common and effective shape on cylindrical parts. The number of turns determines the height of the heated zone. This part can be fixed in the inductor to produce a defined heating band in a "single pass", or it can be moved through the coils to heat completely and very evenly, in a mode called “heating by sweeping or scrolling”. For internal bores, they can be heated using internal inductors at one or several turns.

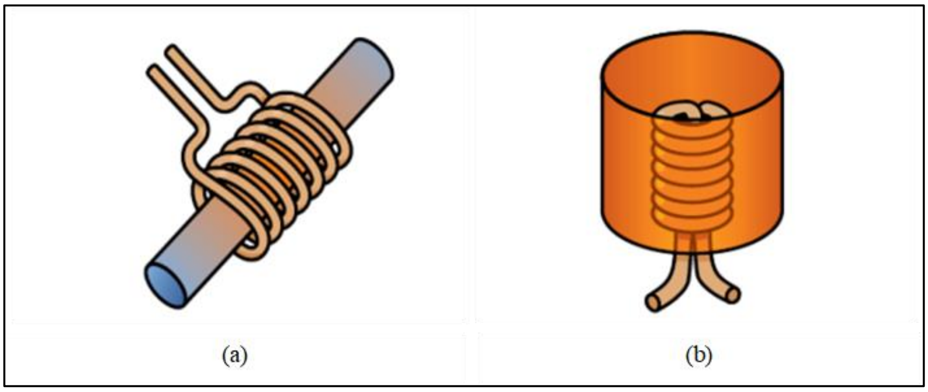

Figure. II. 3 : (a) multi-turn helical inductor, (b)Internal inductor

II.5.2. One-turn inductor (single-turn inductor)

Single turn inductors are ideal for heating narrow or strip ends Room. They can also extend the entire length of a room and are often for heat treatment. These inductors are usually as dense as possible objects to create a precise heating scheme:

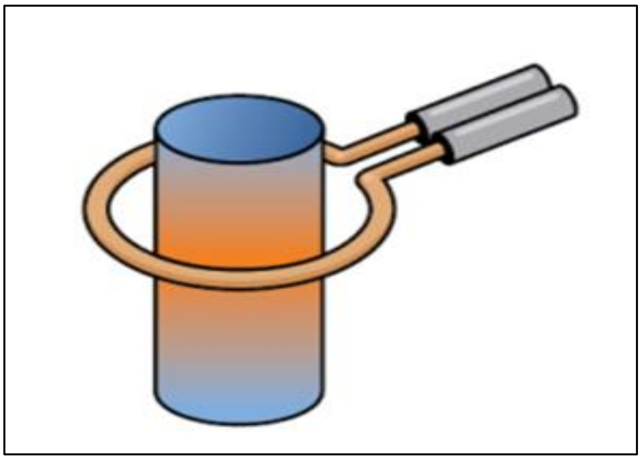

Figure. II. 4: single-turn inductor

II.5.3. Multi-position helical inductor

Multiple sensors are often used to heat more rooms at a given time. While one part is being heated in one location, the other coil can be discharged and charged for the next heating cycle. Where theoretically, it is possible to have any number of coils

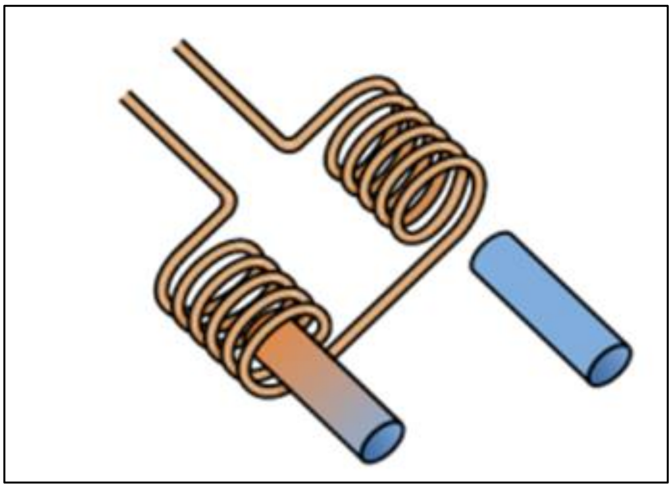

Figure. II. 5: multi-position helical inductor

II.5.4. Tunnel Inductor (Channel Coil)

The shape of the inductor allows the workpiece to be transported through the magnetic field by a linear transport mechanism. The space is heated with duct coils, which can be configured to heat all or part of the space.

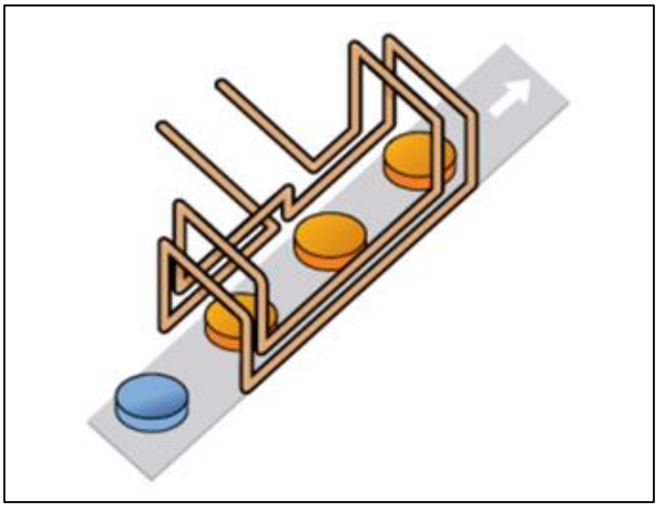

Figure. II. 6: channel coil

II.5.5. Curved channel inductor

The channel inductor can be curved to fit on a turntable and integrate in one of the steps of a multi-step assembly process.

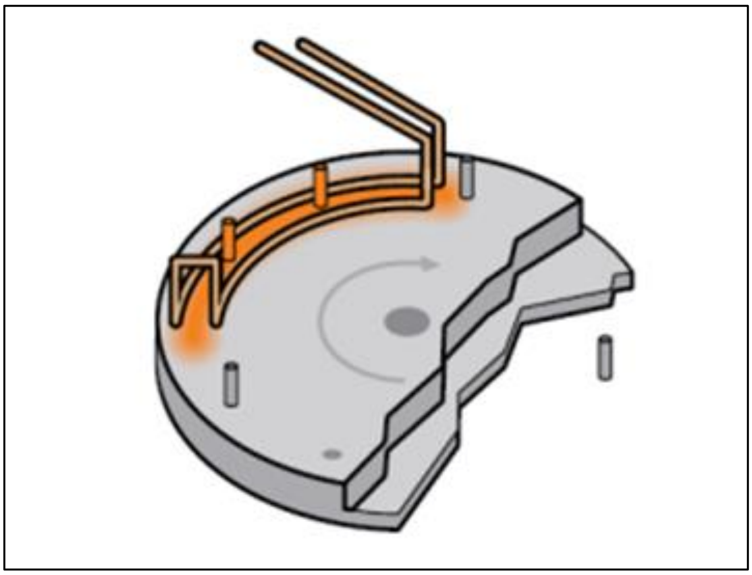

Figure. II. 7: curved channel inductor

II.5.6. Pancakes inductor (Reel in cake)

Pancake inductors are used when the room needs to be heated from one side only or when it is not possible to surround it, this type of inductor is used in hobs.

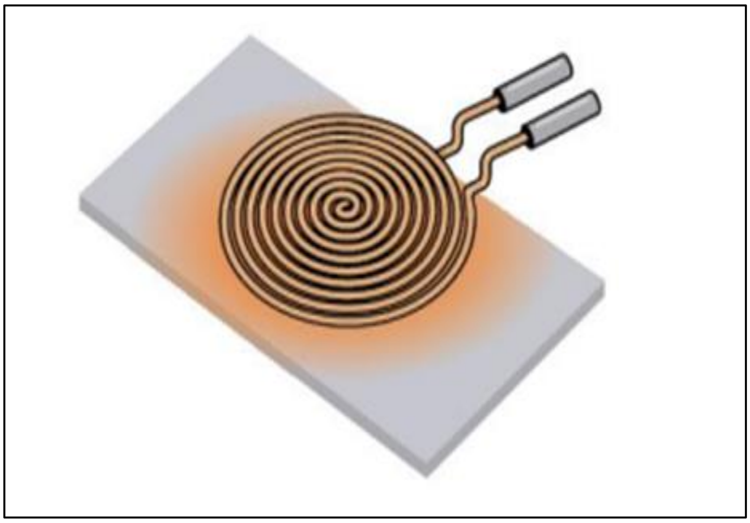

Figure. II. 8: Pancakes inductor

II.5.7. Shared helical inductor (special shape)

Helical inductors shared with one or more turns are used when it is not possible to access the heated area with a conventional solenoid.

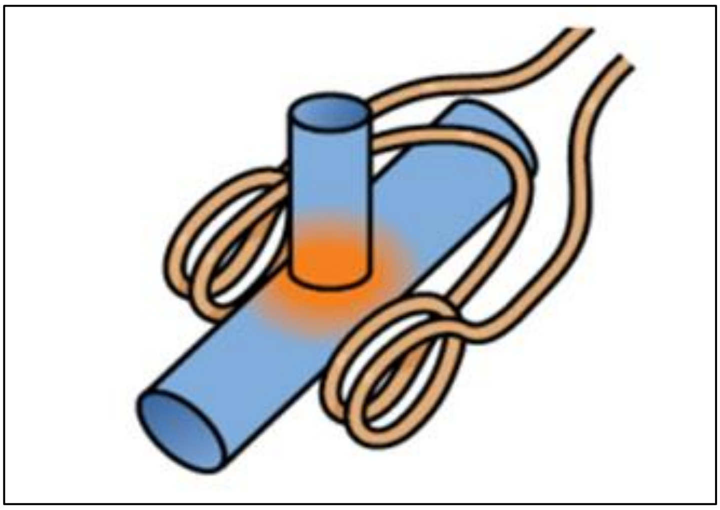

Figure. II. 9: Shared helical inductor

II.5.8. Special form

There are three types of Special Form, concentrating plate inductor Form, reels and conveyors Form, Hairpin inductor Form.

II.5.8.1. Concentrating plate inductor

Concentrated plates are used with single-wind or multi-wind inductors to create a distinct heating effect in a room. These inductors can also have a main inductor with inserts for heating parts of various shapes.

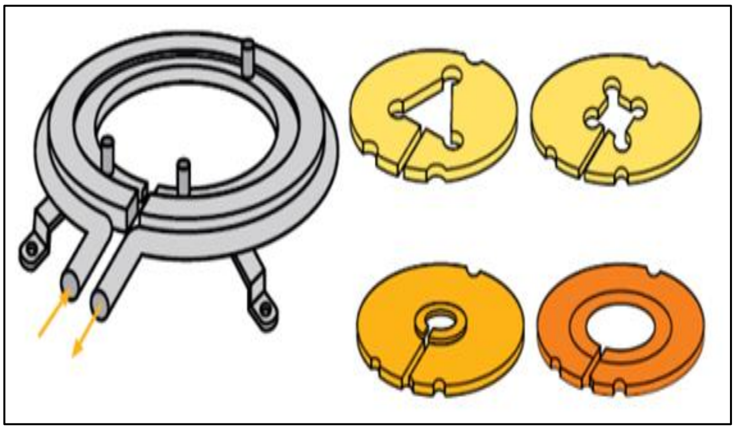

Figure. II. 10: Concentrating plate inductor

II.5.8.2. Reels and conveyors

Many parts heat up during transportation on conveyor systems. As long as the material being transported is not conductive, the magnetic field will penetrate and heat the room.

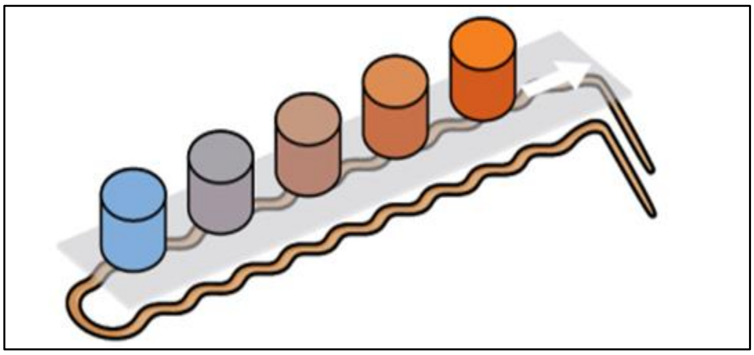

Figure. II. 11: Reels and conveyors

II.5.8.3. Hairpin inductor

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

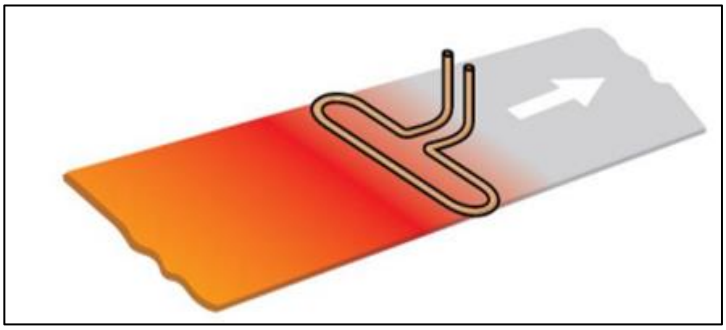

Figure. II. 12: Hairpin inductor

II.6. Induction heating: Joule and hysteresis losses

IH phenomenon is based on two mechanisms of energy dissipation: [11]

II.6.1. Energy losses due to Joule effect

The induction heating takes place when a conductive material is exposed to an electromagnetic field generated by an alternating current. In particular, the magnetic field induces eddy currents on the surface of the material which causes resistive heating due to Joule losses. Different heating mechanisms during induction processing of electrically non-conductive materials, having an internal electrical resistance of infinity, are possible. Therefore, it is necessary to introduce the so called “susceptors” in order to convert a magnetic field into heat. In the case of carbon fiber reinforced materials

II.6.2. Energy losses due to hysteresis

These losses are caused by friction between dipoles when ferromagnetic materials are magnetized in one direction and another. They appear in ferromagnetic materials below their Curie temperature (temperature at which the material becomes non-magnetic). In most of IH applications, hysteresis losses represent less than the 7 % of the eddy current losses. Therefore, eddy currents are the main mechanism of energy dissipation and, so, the most important in IH. [13]

II.7. Inductor-workpiece electrical model

The majority of engineering disciplines require the study of a physical event in order to develop a model that behaves similarly to the actual situation. The goal of this model is to reduce the complexity of the actual issue to a formulation that enables the authors to research the behavior of the phenomena without resorting to a time-consuming iterative approach. This necessity has resulted in numerous models for IH that are based on various simplifications and hypotheses. The inductor-workpiece system is typically portrayed using inductors and resistors in models made for electrical engineers.

The inductor-workpiece system is simplified in this model to an equivalent resistor and inductor, which are more thoroughly explained. [11]

II.7.1. Series and parallel model

Typically, an electrical model of the workpiece and the induction coil is created by an equivalent resistor, Req, and an inductor, L. The series model and the parallel model are the two basic models used to depict the induction coil and the workpiece (**see Figure. II. 13**). [14]

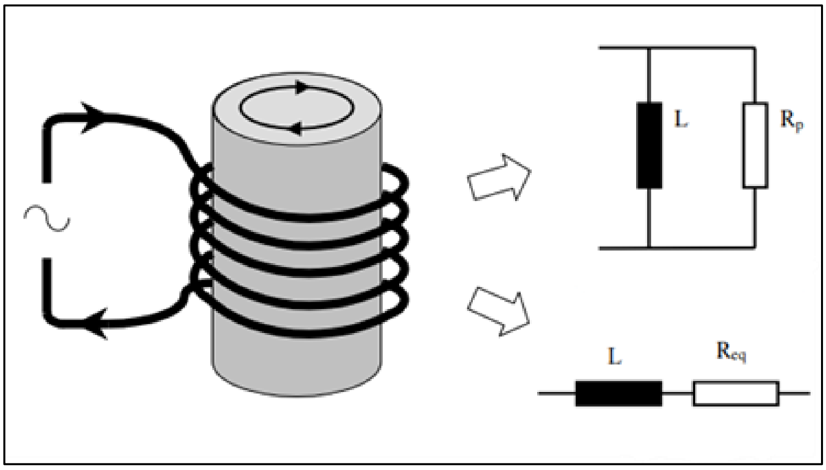

Figure. II. 13: Inductor-workpiece electrical model

- **Series model**

The parameter that best characterizes the RL circuit that constitutes the serial model is the quality factor Q which gives the ratio between the reactive power and active power.

High Q circuit the energy dissipated is much less than the stored one. On the contrary, in a low circuit Q the reactive power is small with respect to the active.

$$\boldsymbol{Q} = \frac{|\boldsymbol{P}_{rect}|}{\boldsymbol{P}_{act}} \qquad \textit{(Eq. II. 1)}$$

for the serial model the power is:

$$\boldsymbol{P} = \frac{1}{2}|\boldsymbol{I}|^2(\boldsymbol{R}_{eq} + \boldsymbol{jL\omega}) = \boldsymbol{P}_{act} + \boldsymbol{jP}_{react} \qquad \textit{(Eq. II. 2)}$$

where I is the current through the circuit, R_{eq} the value of the equivalent resistance connected in series, L the value of the inductance of the coil and w is $2\pi f$ where f is the working frequency therefore, the quality factor for the series model will be.

$$\boldsymbol{Q}_s = \frac{\boldsymbol{L\omega}}{\boldsymbol{R}_{eq}} \qquad \textit{(Eq. II. 3)}$$

- **Parallel model**

Similar to the above, the power of the parallel model is stated as follows:

$$\boldsymbol{P} = \frac{1}{2}|\boldsymbol{V}|^2\left(\frac{1}{\boldsymbol{R}_p} + \frac{1}{\boldsymbol{jL\omega}}\right) = \boldsymbol{P}_{act} + \boldsymbol{jP}_{react} \qquad \textit{(Eq. II. 4)}$$

where V is the voltage applied to the circuit and R_p is the value of the equivalent resistance connected in parallel.

The quality factor for the serial model will have the following value:

$$\boldsymbol{Q}_p = \frac{\boldsymbol{R}_p}{\boldsymbol{L\omega}} \qquad \textit{(Eq. II. 5)}$$

Even though this model is different from the series model, it is shown that the behavior at resonant frequency is equivalent for high quality factors. [14]. In view of this, the energetic behavior is the same in both cases and the following equation is satisfied:

$$\boldsymbol{Q} = \boldsymbol{Q}_p = \boldsymbol{Q}_s \qquad \textit{(Eq. II. 6)}$$

then it is possible to pass from one model to another using the following condition

$$\boldsymbol{R}_{eqp} = \boldsymbol{R}_{eqs}\boldsymbol{Q}^2 \qquad \textit{(Eq. II. 7)}$$

Most authors prefer the series model because it is more straightforward and occasionally simplifies computations owing to the usage of the same current in L and R_{eq}. The series model was adopted in the present study.

II.7.2. Equivalent resistance and inductance Equivalent resistance

- **Equivalent resistance**

The equivalent resistance is the resistance that dissipates the most heat Eddy currents in workpieces [15].so it represents strength dissipated in the workpiece. Take this into consideration and follow it Maxwell's law, it can be shown that in the case of a long solenoid and conductive workpieces, the equivalent resistance is: [16]

$$\boldsymbol{R_{eq} = R_s K_R S_{heated} \frac{N_c^2}{l_\omega^2}} \qquad \textit{(Eq. II. 8)}$$

Where:

- R_s is the superficial resistor of the piece, obtained from

$$\boldsymbol{R_s = \frac{\rho_\omega}{\delta_\omega}} \qquad \textit{(Eq. II. 9)}$$

being ρ_ω the electrical resistivity of the workpiece and δω its penetration depth, explained afterwards in Section

K_R is a dimensionless factor that explains, the equivalent diameter of the piece and the electrical path between penetration depth. This factor is equal to:

$$\boldsymbol{K_R = 1 - e^{\frac{-2r\omega}{\delta\omega}}} \qquad \textit{(Eq. II. 10)}$$

With

- r_ω being the radius of the workpiece.
- S_{heated}, represents the surface heated. It is usually simplified by the perimeter of the piece multiplied by its own length.
- l_ω is the workpiece length.
- N_c are the turns of the induction-coil.

Therefore, for a solid round bar of radius r_ω, the equivalent resistor is equal to:

$$\boldsymbol{R_{eq} = K_R N_c^2 \rho_\omega \frac{2\pi r_\omega}{\delta_\omega l_\omega}} \qquad \textit{(Eq. II. 11)}$$

- **Inductance**

The preceding sections outlined the fundamental principles of electromagnetism, particularly in relation to the transfer of energy between the heating coil and conductive material. We also examined how the agitator's geometry, the heated substance's properties, and the frequency of work affect the equivalent resistance and heating capacity. Moving forward, we'll examine the coil cutting set's equivalent circuits, which will facilitate the analysis of this group utilizing grid theory, value becomes [17]

$$\boldsymbol{L \approx \frac{10\pi\mu_0 N_c^2 r_c^2}{9r_c + 10l_c} = 3.9410^{-5}\frac{d_c^2 N_c^2}{18d_c + 40l_c}} \qquad \textit{(Eq. II. 12)}$$

Where

- L is the inductance value.
- $l_c$is the coil length.
- r_c is the radius and dc the diameter.
- μ_0 is the magnetic permeability of the vacuum, which is equal to $4\pi \cdot 10^{-7}$H/m.

II.8. Efficiency

Heating by Induction has minimal wasted heat, with direct transfer of energy to the part being heated. This high efficiency results in significant power savings. Induction heating proves to be a highly efficient method for industrial heating applications. [11]

II.8.1. Penetration depth and critical frequency

When an alternating current flow through a conductor, the current distribution within its cross-sectional area is not uniform. In IH, the currents that create heat in the workpiece are not continuous and its distribution is not uniform. When a wire is heated by a solenoid, it causes currents to flow in the workpiece which generate a magnetic field that resists the original magnetic field. This results in the two magnetic fields effectively nullifying each other, which weakens the magnetic field at the center. As a result, the induced currents in the center are relatively smaller. Eddy currents tend to concentrate in the surface layer of a workpiece due to a phenomenon called the skin effect. This causes the currents to flow closer to the surface, as illustrated in (**Figure. II. 14**), [18]

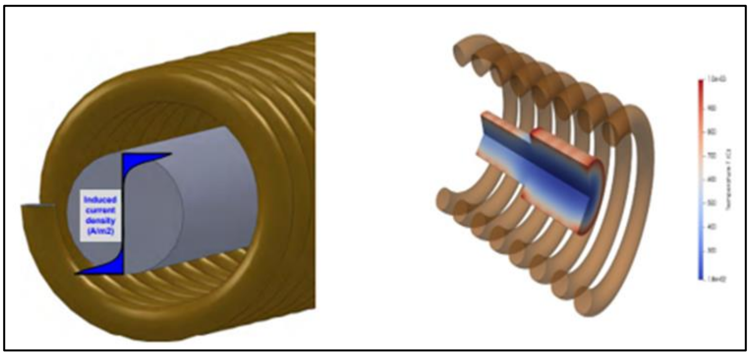

Figure. II. 14: Penetration depth and critical frequency

II.8.2. Inductor-workpiece coupling

Regarding the transmission efficiency due to the coupling between Inductors and workpieces, the narrower the diameter the better. This The smaller the distance between the inner diameter of the coil and the workpiece, the more and more magnetic force lines passing through the workpiece Energy transfer is efficient. However, there is a gap between the two diameters Inductive short circuits need to be avoided. refractory in some cases Material is introduced between the coil and the workpiece. This material avoids short circuit, but also reduces heat loss through radiation or convection the diameter of the inductor and the thickness of the refractory are. The tradeoff between the worst-case coupling loss and the loss due to coupling surface heat loss. [13]

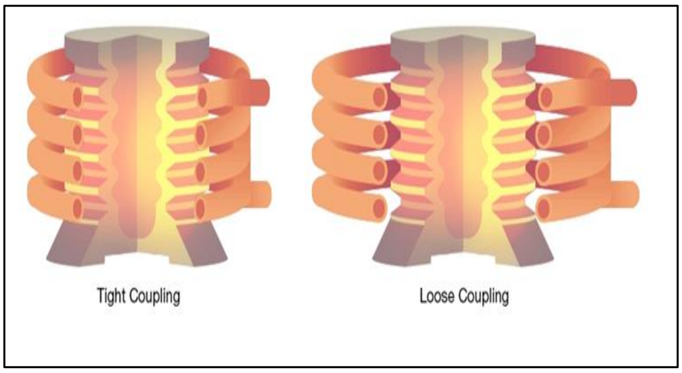

Figure. II. 15:Inductor-workpiece coupling

II.9. Estimation of the inductor and power supply requirements

Once the workpiece (shape and material) and heat treatment (temperature and production rate) are defined, the frequency needs to be defined. The length of the process, the length of the coil and the power requirements of the converter that powers the resonant tank. Considering previous sections, this section aims to provide a brief overview of the procedure the designer follows to determine the inductor and performance converter requirements.

II.10. Power requirements

The power needed to heat a workpiece to a given temperature is [13]

$$\boldsymbol{P_{\omega} = \frac{mc\left(T_{final} - T_{initial}\right)}{t}} \qquad \textit{(Eq. II. 13)}$$

Where

- P_{ω} is the workpiece power.
- m is mass of the workpiece.
- T_{final} and $T_{initial}$ are the average values of initial and final temperatures.
- c is the average value of the specific heat of the material.
- t is the required heating time.

II.11. Thermal efficiency

The efficiency of electromagnetic energy transfer. Using the analytical model, the influence of various parameters such as potentiometer characteristics, number of windings turns, current frequency, arrangement of cable types was examined. Thermal efficiency includes surface losses due to radiation and convection, and those due to conduction at the ends of the coil. these losses may be reduced due to refractory insulation, but it must carefully design to avoid electromagnetic coupling degradation. This results in increased electrical losses. For cylindrical coils with concrete as refractory material, the following formula applies. [13]

$$\boldsymbol{P_{thermal} = \frac{P_{\omega}}{P_{\omega} + P_{thermalosess}}} \qquad \textit{(Eq. II. 14)}$$

And

$$\boldsymbol{P_{thermalosess} = 3.74.10^{-4}\frac{l_c}{log_{10}(\frac{d_c}{d_{\omega}})}} \qquad \textit{(Eq. II. 15)}$$

where

- $P_{thermalosess}$ are thermal losses through the surface.
- d_c and d_{ω} are the inside coil diameter and workpiece diameter, respectively.
- l_c is the coil length.

II.12. Electrical efficiency

Heat should not be confused with or synonymous with thermal energy. Although they are closely related to heat, they are different physical entities. As a heating technology, Joule heating has a coefficient of performance of 1.0, which means that for every joule of electrical energy supplied, one joule of heat is produced. Electrical efficiency represents the number of coils turns and losses in the environment. as A first approximation when heating a solid cylinder in a long magnetic coil, the following formula can be used [13]

$$\boldsymbol{\eta_{el}} = \frac{\mathbf{1}}{\mathbf{1} + \frac{\boldsymbol{d_c + \delta_c}}{\boldsymbol{d_\omega - \delta_\omega}}\sqrt{\frac{\boldsymbol{\rho_c}}{\boldsymbol{\mu_r \rho_\omega}}}} \qquad \textit{(Eq. II. 16)}$$

where

- $\delta_c$and δ_ω are coil and workpiece's penetration depth, respectively.
- ρ_c and ρ_ω are coil and workpiece's electrical resistivity, respectively.
- μ_r is the relative magnetic permeability of the workpiece.

II.13. Conclusion

IH is a heating method for electrically conductive materials that utilizes the heat losses resulting from eddy currents. Although hysteresis losses also generate heat during the process, they do not significantly contribute in the case presented.

In IH systems, the inductor-workpiece system is electrically modeled using an inductor and a resistor, which can be connected in series or parallel. The quality factor Q, which represents the ratio between reactive and active power, is used to compare the parallel and series models. While both models are valid, the series model is employed in this study.

The efficiency of power transmission from the inductor to the workpiece is influenced by the frequency and the inductor-workpiece geometry. Choosing a low frequency value leads to cancellation of eddy currents in the workpiece, resulting in a significant decrease in power transmission efficiency.

The efficiency of the process is also affected by the coupling between the inductor and the workpiece. When the distance between the internal diameter of the coil and the workpiece is minimal, most of the magnetic field lines cross the workpiece, leading to increased efficiency.

Considerations are also given for determining the length of the coil, taking into account the limits of the converter and the maximum allowed current in the coil.

Chapter III:

Induction heating converters

III.1. Introduction

In this chapter, an introduction to the modeling and simulation of induction heating systems is presented. The importance of using mathematical models to understand the behavior and interactions of the system components is emphasized. The use of physical and electromagnetic equations in the design of mathematical models is highlighted.

The significance of numerical simulation in running the mathematical models and analyzing the results in an interpretable manner is also discussed. The benefits of using modeling and simulation in evaluating the performance of induction heating systems and improving their design are explored.

Finally, some tools used for modeling and simulation, such as MATLAB, Simulink, are mentioned.

In summary, the use of modeling and simulation is a powerful approach for understanding and analyzing induction heating systems, and it contributes to enhancing system design and achieving optimal performance.

III.2. Power semiconductor

Advances in semiconductors have made it possible to develop these structures Both in terms of frequency and in terms of the use of the natural switch, with blocking control. Although the thyristor is the most responded component Induction, the "thyristor" function can be synthesized with other semiconductors quickly. The above components involved in all electronic applications strength.

- **Diode**

The first electronic power components appeared in 1956: power diodes to silicon. They allow current to flow in one direction only, like check valves used with fluids. Although these devices are simple and very useful, they have some disadvantages: [19]

- threshold voltage
- dynamic resistance
- parasitic capacitance

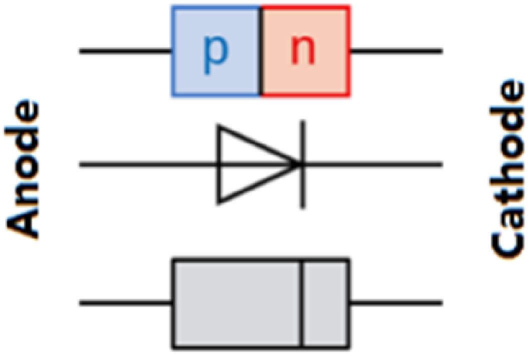

Figure. III. 1 : Diode

- **MOSFETs**

MOSFET (Metal Oxide Semiconductor Field Effect Transistor) transistors are mostly used for low powers. They are excellent replacements for bipolar transistors because they are very fast and their control is simple. The main feature is that the blocking and priming are controlled by a voltage.

MOSFETs are limited to applications requiring a few hundred volts at most. Admittedly, they have a non-negligible on-state resistance which produces losses by conduction. On the contrary, they are very fast and are used in high frequency converters [20] [21]

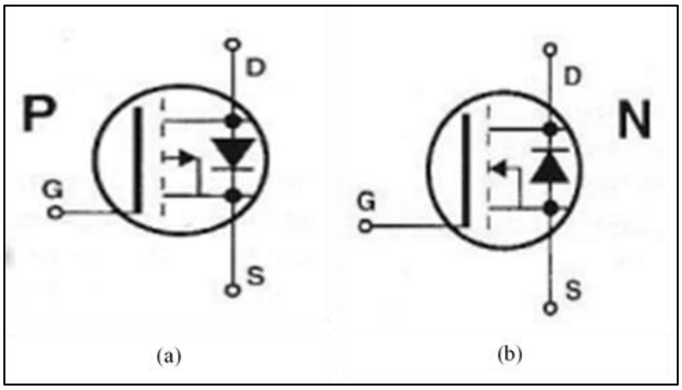

Figure. III. 2 : (a) MOSFET canal P, (b) MOSFET canal N

- **Bipolar transistor**

Shortly after the invention of thyristors, power bipolar transistors were developed and they allowed the design of electronic converters of low and medium power. In the 80s they were used enormously and they left no room for thyristors only for very high-power applications above 1 MW, or voltages voltage greater than 2kV. The disadvantages of these switches are that they require a complicated control circuit and have poor dynamic performance compared to other devices. However, they are thermally more stable and above all, because of their current control, they are less sensitive electromagnetic noise [22] [23]

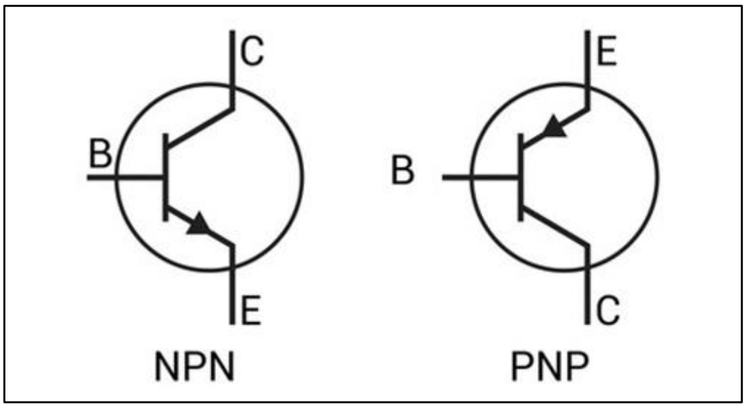

Figure. III. 3 : Bipolar transistor

- **IGBT Transistor: Insulted Gate**

Another wave of devices still widely used came in 1983: these are the IGBTs (Insulated Gate Bipolar Transistor). They allowed the manipulation of powers in the beginning averages, replacing the Darlington transistors. Nowadays, these transistors are also used for high power applications. IGBTs are hybrid circuits, they combine the convenient characteristics of MOSFETs and bipolar transistors. They are therefore quick and easy to order, with good resistance to voltage and low on-state resistance. Since the 1990s, they have been widely used in the design of converters operating at voltages from a few hundred volts to a few kilovolts and with currents ranging from a few tens of amperes to a few kilo-amperes [24]

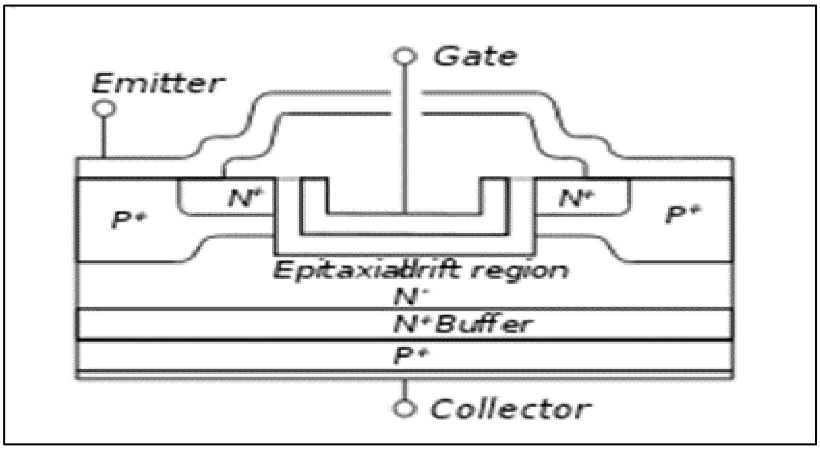

Figure. III. 4 : IGBT Transistor

- **Thyristor**

It is the most widespread component in induction, because the oldest, it allows the Conversion of high-power converters up to a few kHz. Only controllable at the start, it is not necessary to implement a natural switching structure or a blocking circuit (no need for induction, thanks to the resonant circuit). [25]

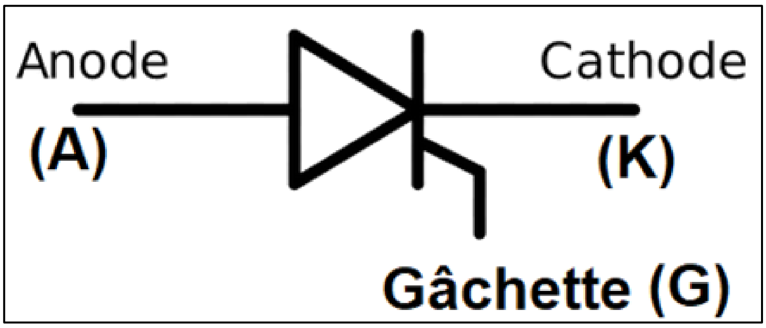

Figure. III. 5 : Thyristor

- **Thyristor GTO**

The GTO thyristor is a generally asymmetrical thyristor, which can be switched off by the trigger. The interdigital structure of the trigger allows charges to be evacuated during blocking. This blocking is nevertheless a loss generator and a SSC at the opening is necessary.

This component is particularly developed in high power (a few kA - a few kV) but is still little used in induction. It should replace the conventional thyristor in the rectification system: [25]

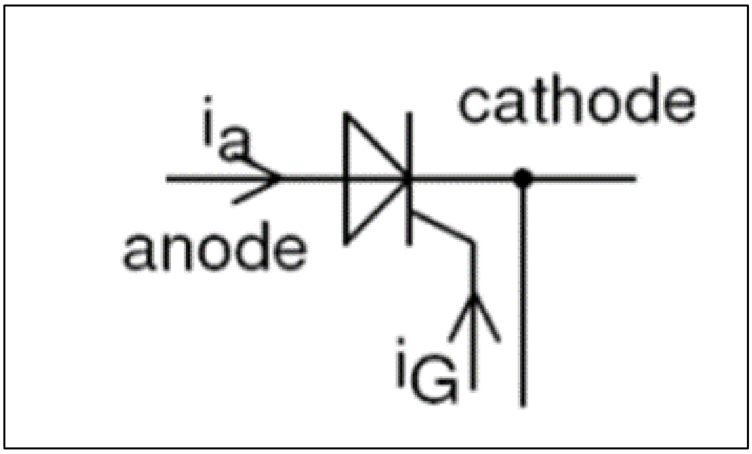

Figure. III. 6 : Thyristor GTO

III.3. Complete block diagram of the induction heating system

An induction heating system generally consists of several components that work together to generate and deliver high-frequency electromagnetic energy to heat the target material. Here is a complete block diagram of the induction heating system:

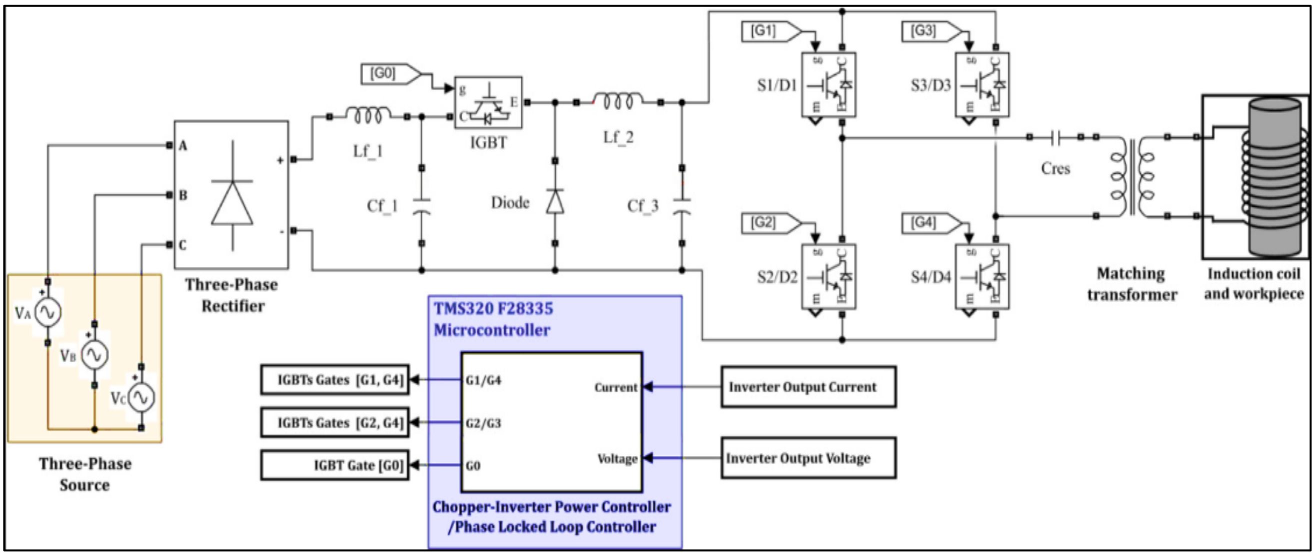

Figure. III. 7 : Complete block diagram of the induction heating system

III.4. The rectification system

Three-phase rectification can be achieved in double alternation by using a three-phase Graetz bridge. It consists of 6 diodes, followed by a capacitor to filter the voltage.

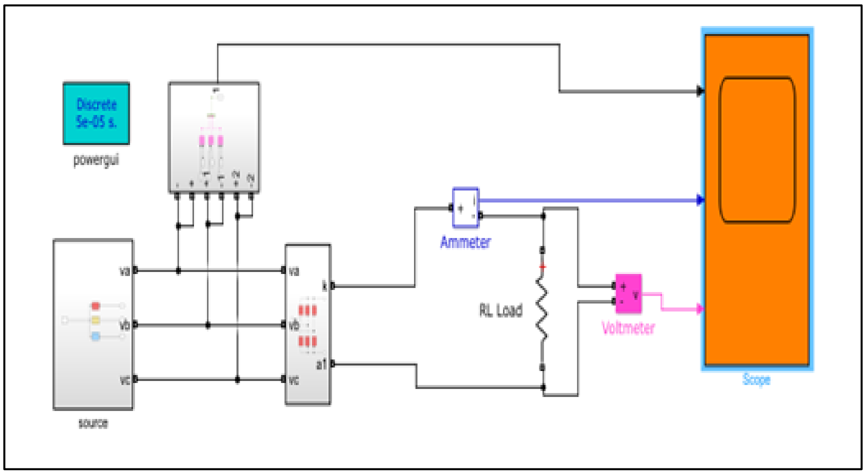

Figure. III. 8 : Equivalent circuit diagram of a three-phase rectifier

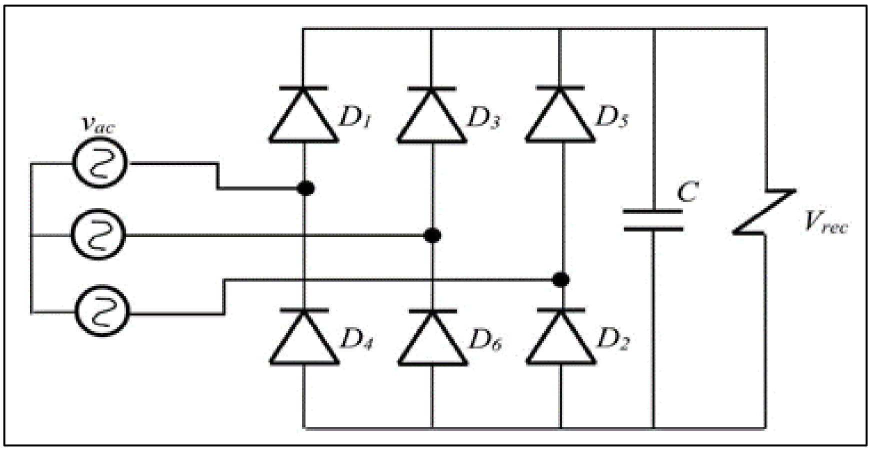

Figure. III. 9 : three-phase rectifier diagram

When the voltages V_1, V_2, and V_3 are given, they are considered voltages between phase and neutral (single-phase voltages) with an effective value of V_{eff}. The Max and Min functions ensure the following:

Among the diodes D_1, D_3, and D_5, the diode with the most positive voltage on its anode conducts.

Among the diodes D_2, D_4, and D_6, the diode with the most negative voltage on its cathode conducts.

Let's assume we have the following three-phase system:

$$\boldsymbol{V_1 = V\sqrt{2}sin(\omega t)} \qquad \text{(Eq. III. 1)}$$

$$\boldsymbol{V_2 = V\sqrt{2}sin(\omega t - \varphi)} \qquad \text{(Eq. III. 2)}$$

$$\boldsymbol{V_3 = V\sqrt{2}sin(\omega t - 2\varphi)} \qquad \text{(Eq. III. 3)}$$

We set $T = \varphi$, which is the period of these voltages. Between 0 and T, the voltage V_3 is the highest and the voltage V_2 is the lowest. Therefore, diodes D_5 and D_6conduct, and the output voltage V_s is the voltage U_{32} between phases 3 and 2. Between T and 2T, the voltage V_1 is the highest and the voltage V_2 is the lowest. Therefore, diodes D_1 and D_6 conduct, and the output voltage V_s is the voltage U_{12} between phases 1 and 2

Between 0 and T, the voltage V_1 is at its maximum and the voltage V_3 is at its minimum. Therefore, diodes D_1 and D_2 conduct, and the output voltage V_s is equal to the voltage U_{13} between phases 1 and 3.

- **Calculating the average value of the output voltage**

The output voltage consists of portions of sinusoids with an effective value of V√3. The output voltage is periodic with a period T/6. Let's calculate the average value, for example, when diodes D_1 and D_2 conduct.

The average value of the output voltage is then:

$$\boldsymbol{V_s(t) = \frac{1}{\frac{T}{6}} \int_{-\frac{T}{12}}^{\frac{T}{12}} u_{12}(t)dt = \frac{3\sqrt{3}\,\sqrt{2}}{\pi}\, V.2\sin\left(\frac{\pi}{6}\right)} \qquad \text{(Eq. III. 4)}$$

Finally

$$< \boldsymbol{V_s(t)} >= \boldsymbol{\frac{3\sqrt{6}}{\pi}\, V} \qquad \text{(Eq. III. 5)}$$

- **Waveforms with and without capacitance**

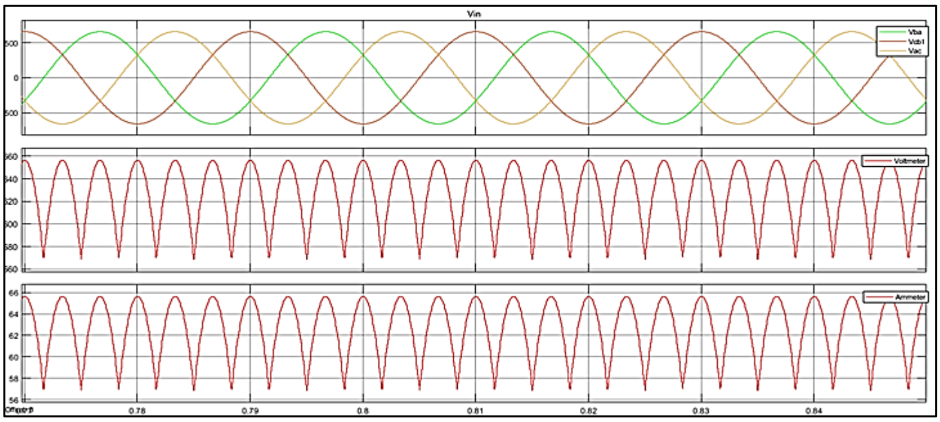

Figure. III. 10 : Waveforms with and without capacitance

III.5. Modeling of the chopper

Choppers are static DC-DC converters that allow delivering an adjustable DC voltage from a constant DC voltage source. A chopper enables the control of energy transfer from a DC source to the load with high efficiency. Depending on the structure, it can be a step-down (buck) or a step-up (boost) converter, and under certain conditions, it can also return energy back to the power supply. The diagram of this static converter is given in (**Figure. III. 11**)and (**Figure. III. 12**)

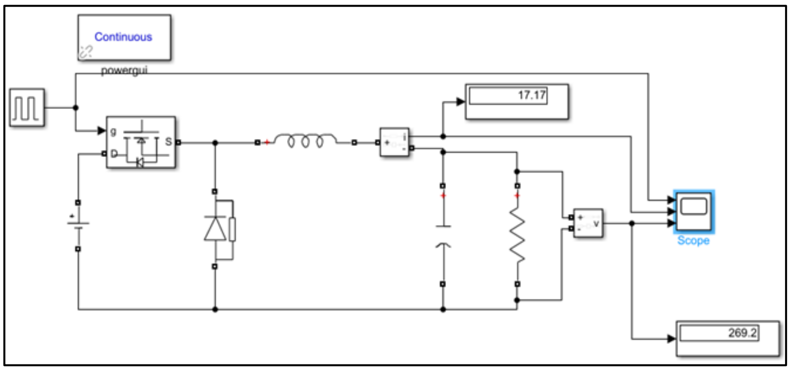

Figure. III. 11 : Equivalent circuit of a series chopper

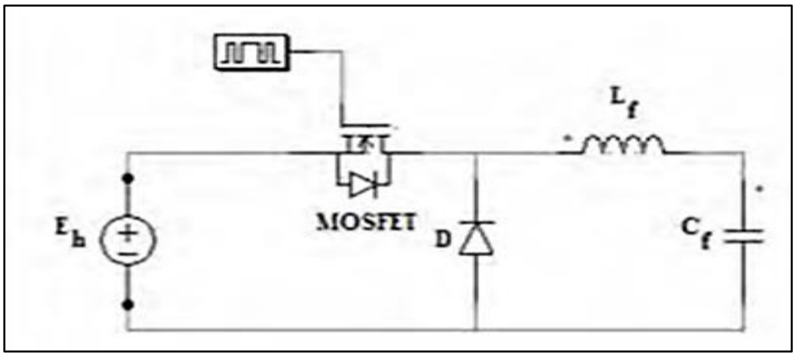

Figure. III. 12 : schematic diagram of a series chopper

III.5.1. Principle of a series chopper or buck converter

The operation is at a switching frequency $f_c = \frac{1}{t}$, where T is the switching period of the transistor switch. When the MOSFET is conducting, with the diode blocked, the output voltage Vs across the diode will be equal to the input voltage Eh. The series chopper has two different operating modes, illustrated by (**Figure. III. 13**) and (**Figure. III. 14**):

During the first-time interval $[0;\ \alpha T]$, the MOSFET is on and the diode is off.

$$\boldsymbol{E_h = L_f.p.i_e(p) + V_s(p)} \qquad \text{(Eq. III. 6)}$$

$$\boldsymbol{i_e(p) = C_f.p.V_s(p) + \frac{V_s(p)}{R_{ch}}} \qquad \text{(Eq. III. 7)}$$

This leads us to the following equations:

- E_h: input voltage
- L_f: filter inductance
- C_f: filter capacitance
- i_e: input current
- V_s: output voltage
- R_{ch}: load resistance
- p : Laplace operator

During the second time interval $[\alpha T;\ T]$, the MOSFET turns off and the diode becomes conducting, which corresponds to a new circuit.

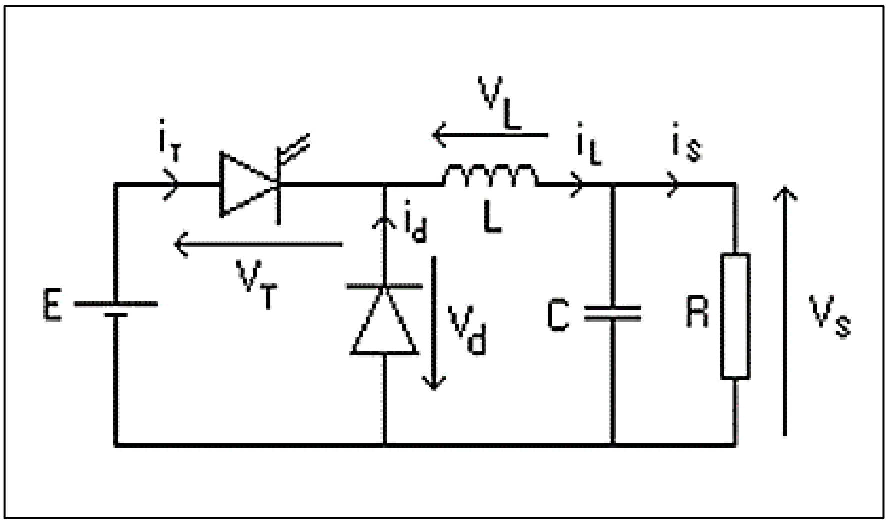

Figure. III. 13 : Power supply mode

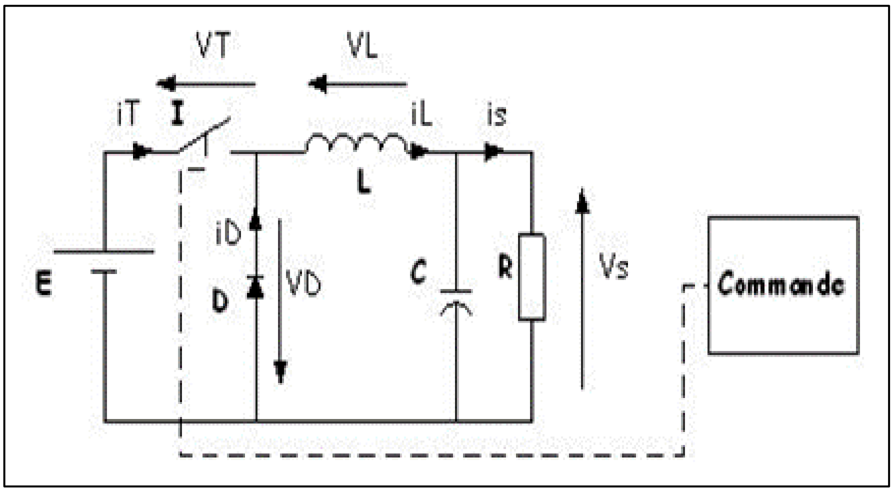

Figure. III. 14 : Free-running mode

In this mode, we consider only E equal to zero in (Eq. III. 6). Here is a representative diagram of the conduction timing of the series chopper in the (**Figure. III. 15**).

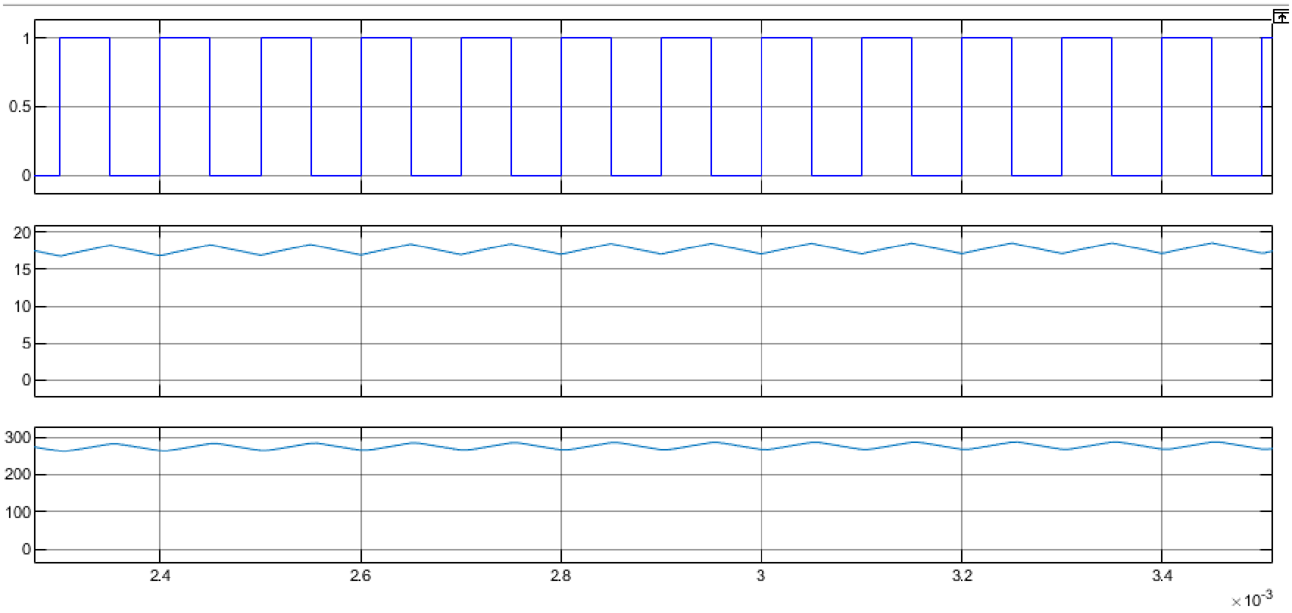

Figure. III. 15 : Conduction timing diagram

The low-pass filter (LC) transmits to the load the average value of the output voltage Vs and also rejects the undesirable harmonics of this voltage. However, the load voltage V_{ch} is the superposition of the desired value with residual ripples.

The load voltage is equal to the average value of the output variable of the chopper, which is the voltage at the input of the (LC) filter represented by the area of the square waveform obtained during one cycle divided by the switching period. This can be expressed by the following relationship.

$$\boldsymbol{V_s = \frac{1}{T}\int_0^T v_s\, dt = \frac{1}{T}\int_0^{\alpha T} E_h\, dt} \qquad \text{(Eq. III. 8)}$$

Where α is the duty cycle.

III.6. Modeling of the inverter

Inverter modeling is the process of creating a mathematical model that simulates the behavior of an electrical inverter. This is achieved by identifying the key physical parameters and selecting the appropriate model type.

III.6.1. Type of resonance converter

There are several types of resonance converters, including: [26] [27]

- **Voltage-Fed Series Resonant Inverter (VFSRI)**

In an VFSRI, the primary side of the converter is connected in series with a resonant circuit consisting of an inductor and a capacitor. This configuration allows for soft switching and high-frequency operation.

- **Current-Fed Parallel Resonant Inverter (CFPRI.)**

In a CFPRI., the primary side of the converter is connected in parallel with a resonant circuit. This configuration also enables soft switching and high-frequency operation.

- **LLC Resonant Converter**

The LLC converter is a type of resonant converter that uses a combination of inductance (L), capacitance (C), and leakage inductance (L) for soft switching. It is known for its high efficiency and low electromagnetic interference (EMI).

- **Half-Bridge Resonant Converter**

This type of resonant converter uses a half-bridge configuration, where two switches are connected in series with the primary side and the resonant circuit. It offers benefits such as high-power density and improved efficiency.

- **Full-Bridge Resonant Converter**

In a full-bridge resonant converter, four switches are used in a bridge configuration along with a resonant circuit. It provides bidirectional power flow and is commonly used in applications such as electric vehicle charging and renewable energy systems.

These are just a few examples of resonance converters, and there are other variations and hybrid topologies available. The choice of the converter depends on specific application requirements and constraints.

And the following study we made selections Voltage-Fed Series Resonant Inverter (VFSRI)

III.6.2. Advantages of a Voltage-Fed Series Resonant Inverter (VFSRI) [28]

- **High Efficiency:** Utilizing series resonance in an VFSRI allows for high energy conversion efficiency. The soft switching operation reduces switching losses and improves overall efficiency.
- **Compact Size:** VFSRI can be designed to operate at high frequencies, allowing for the use of smaller and lighter passive components such as inductors and capacitors. This results in a more compact and space-efficient converter design.
- **Reduced Electromagnetic Interference (EMI):** The soft switching characteristics of an VFSRI help to minimize high-frequency switching noise and EMI emissions. This makes VFSRI suitable for applications with strict EMI requirements.
- **Improved Power Quality:** VFSRI can provide improved power quality due to their ability to regulate output voltage and maintain stability even under varying load conditions. This makes them suitable for sensitive electronic equipment and applications that require stable and clean power supply.
- **Wide Voltage Range Operation:** VFSRI can be designed to operate efficiently over a wide input voltage range, making them suitable for applications with varying input voltage levels, such as renewable energy systems.
- **Bidirectional Power Flow:** With appropriate control strategies, VFSRI can support bidirectional power flow, allowing energy to be transferred both from the input source to the load and vice versa. This feature is useful in applications such as energy storage systems and regenerative braking. It’s important to note that the specific advantages of an VFSRI may vary depending on the design, application, and operating conditions. Proper design, control, and component selection are crucial to harnessing these advantages and optimizing the performance of an VFSRI.

III.6.3. Modeling of the voltage inverter

A voltage inverter is a DC/AC converter. Its diagram is a single-phase bridge.

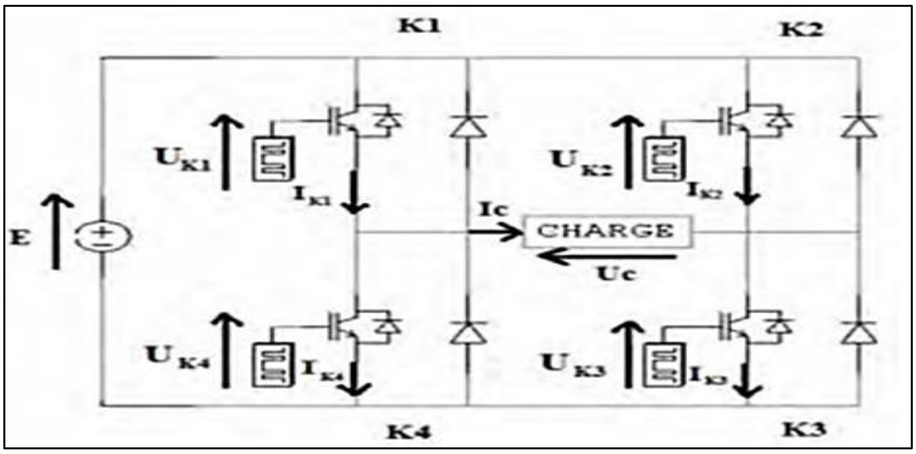

Figure. III. 16 : single-phase inverter diagram

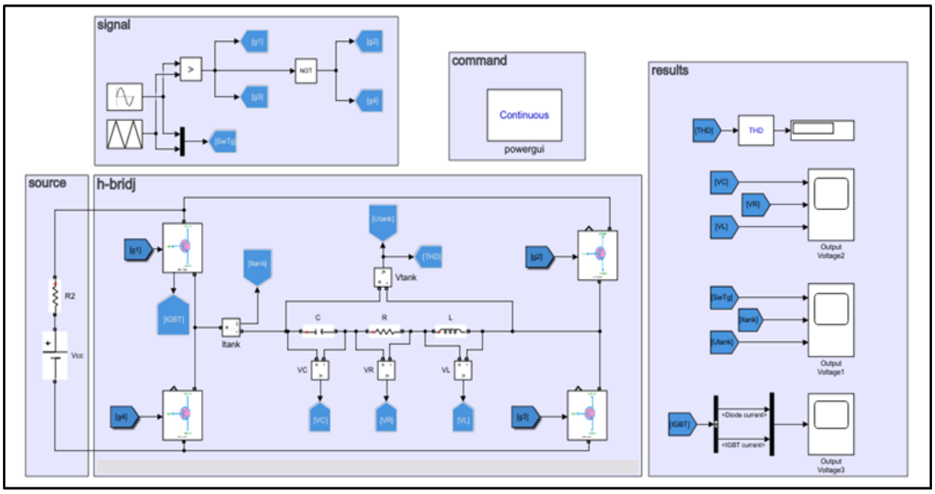

Figure. III. 17 : Equivalent circuit diagram of a single-phase inverter

III.6.4. Characteristics of series inverters

The capacitor is placed in series with the load, so that the charge itself behaves as a source instantaneous current. Therefore, a resonant inverter powering this load is voltage inverter. Series inverters require asymmetric voltage components, which are now available in a wider range of options. Analysis of inverter arm switching phenomena, the voltage shows that switching at actuation is more constraining than controlled switching at locking, mainly because the technology is not perfect. Components (diode recovery current, dV/dt...)

III.7. Voltage-fed series resonant inverters

In series resonant tanks, the inductor is connected in series with the capacitor. In this configuration, the tank acts as a current source, and a voltage-fed inverter is used, meaning that the inverter is supplied with a constant voltage source. This requires the use of a high-capacitance capacitor to maintain a constant voltage. (**Figure. III. 18**) illustrates a series tank and an ideal Voltage-Fed Series Resonant Inverter (VFSRI).

For applications above 5 kW, the most commonly used inverter is the H-bridge, as shown in (**Figure. III. 18**) This topology allows the transmission of the same power with less current for a given voltage (U_e). Since the application in this study involves industrial heating of round wires, where the converters have power ratings of tens of kilowatts or more, the H-bridge structure is commonly employed throughout the study**.** [29]**,** [30]

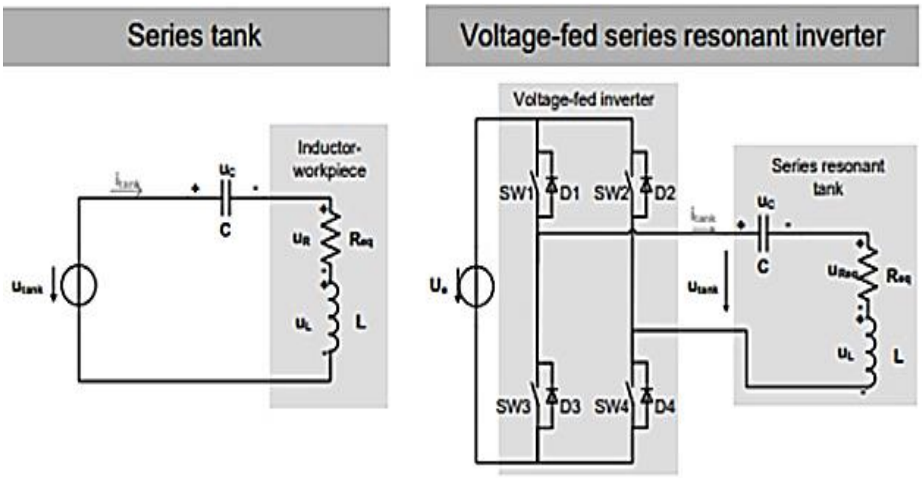

Figure. III. 18 : Series tank and a VFSR

In voltage-fed inverters, it is essential to avoid turning on two switches of the same inverter leg simultaneously to prevent a short circuit. A dead-time, which is the time between turning off one switch and turning on the other, is introduced to ensure proper operation. Additionally, antiparallel diodes are necessary in this topology to allow the conduction of inductor current when the opposite switches are turned off.

in that section, it is assumed that switches SW1 & SW4 and SW2 & SW3 alternate in commutation with a duty cycle of 50%, and power control is achieved by varying the voltage of the source U_e as shown in (**Figure. III. 18**)

III.8. Resonant frequency

The resonant frequency ωr is defined as the frequency at which the maximum module of a transfer function occurs [31], Observing the RLC circuit of a VFSRI in (**Figure. III. 18** : Series tank and a VFSR), the following equation is accomplished:

$$\boldsymbol{u_{tank} = u_{Req} + u_L + u_C = R_{eq} i_{tank} + L\frac{di_{tank}}{dt} + \frac{1}{C}\int i_{tank} dt} \quad \text{(Eq. III. 9)}$$

$$\boldsymbol{U_{tank}(s) = R_{eq} I_{tank}(s) + sLI_{tank} + \frac{1}{sC} I_{tank}(s)} \quad \text{(Eq. III. 10)}$$

Obtaining the following second order system with a zero:

$$\boldsymbol{H_s(s) = \frac{I_{tank}(s)}{U_{tank}(s)} = \frac{sC}{s^2LC + sCR_{eq} + 1} = sC\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}} \quad \text{(Eq. III. 11)}$$

(**Figure. III. 19**) illustrates the Bode analysis of the transfer function $H_s(\omega)$. The circuit consists of an Req of 1558 mΩ, an L of 9.78 μH, and a C of 0.26 μF. The graph shows a single peak at approximately 100 kHz, which represents the resonant frequency. At the resonant frequency, the impedance is minimized, indicating maximum current flow and heat generation in the workpiece when a voltage with the resonant frequency is applied. These oscillatory circuits are preferred in induction heating applications as they allow high currents with low voltages.

Additionally, at the resonance frequency, the impedance equals Req. This results in the cancellation of the inductive and capacitive components, causing the voltage and current to be in phase. Consequently, switching losses are theoretically reduced to zero because the current approaches zero during commutation. This advantageous commutation process, known as soft-switching, allows IH converters to operate at higher frequencies compared to conventional hard-switching methods.

Soft-switching involves two mechanisms: zero voltage switching (ZVS) during switch turn-on, where the switch is activated with zero voltage, and zero current switching (ZCS) during switch turn-off, where the semiconductor turns off without current flow. These concepts are frequently used to explain the commutation mechanisms in IH converters

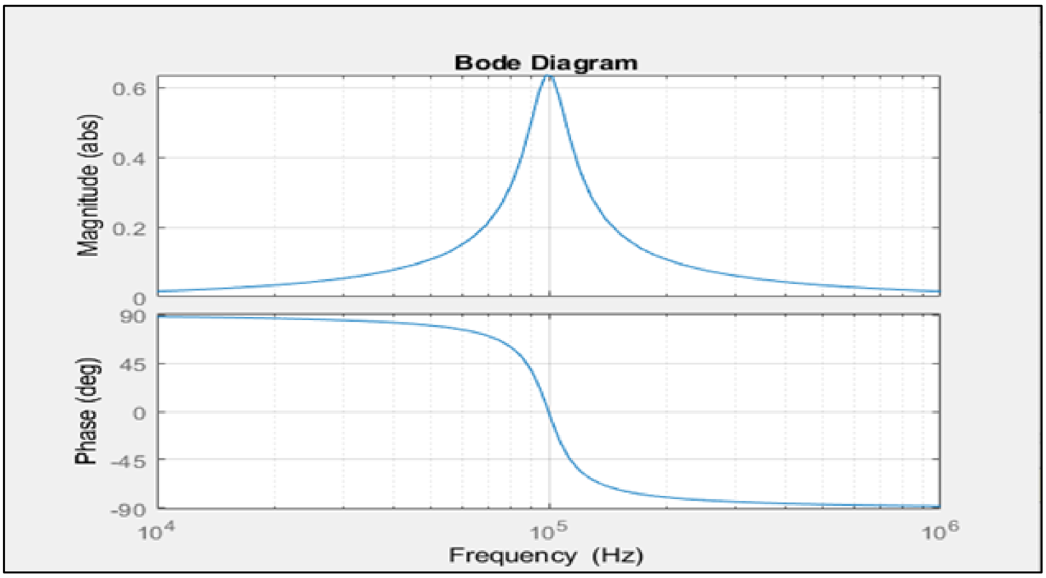

Figure. III. 19 : Bode analysis of the transfer function Hs(ω) with Req = 1558 mΩ

III.8.1. Quality factor

The relationship between the quality factor (Q) and the electrical parameters is discussed in this section. The quality factor is defined as the ratio between the reactive power and the active power of the inductor-workpiece system. Firstly, the section explains the correlation between the quality factor and the current waveform. Secondly, it discusses the connection between this factor and the voltage across the components of the tank.

- **Quality factor and current:** Considering that the converter is commutating at resonant frequency, the quality factor, is equal to:

$$\boldsymbol{Q = \frac{|P_{rect}|}{P_{act}}} \qquad \text{(Eq. III. 12)}$$

As the RLC circuit of the tank is a second order system, it becomes more undamped and oscillatory as the imaginary part of the roots increases and the real part decreases [31]

In (**Figure. III. 20**), the Bode analysis of the transfer function $Hs(\omega)$ ((Eq. III. 11)) is shown for three different resonant tank circuits. These circuits have the same inductance (9.78 µH) and capacitance (0.26 µF), but they vary in the value of Req, which takes the values of 15.58 Ω, 3.58 Ω, and 1.58 Ω. The corresponding quality factor (Q) values for these cases are 0.39, 1.71, and 3.88. In (**Figure. III. 21,Figure. III. 22,Figure. III. 23**), the time response of U_{tank} and $itank$ is displayed for these three different cases, operating at the resonant frequency where the commutation frequency (f_{sw}) is equal to the resonant frequency (f_r).

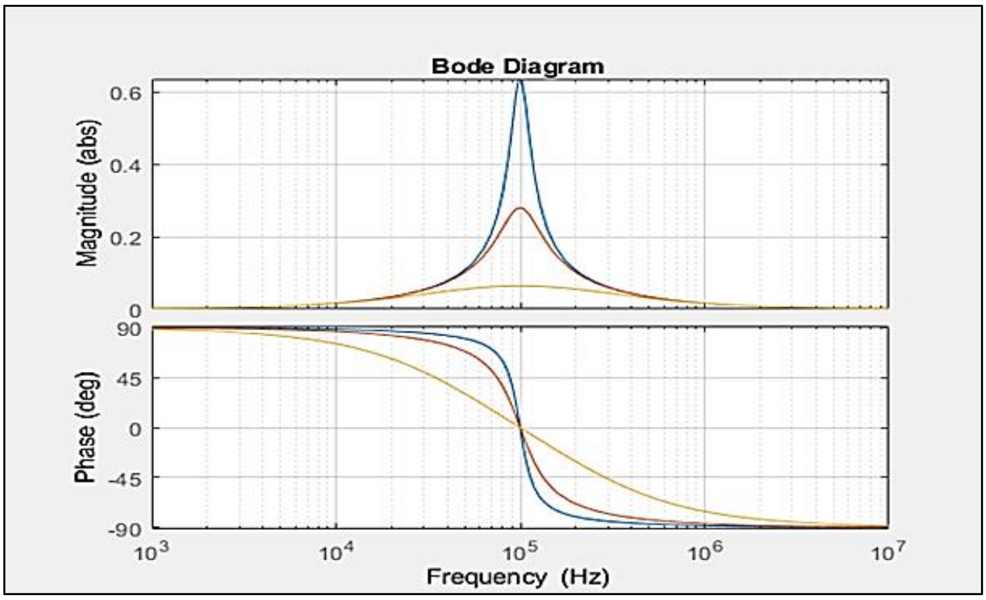

Figure. III. 20 : Bode analysis of the transfer function Hs(ω) for three systems with different Q values

In (**Figure. III. 20**), it can also be observed that the peak value increases as the Q value increases. This is logical because the peak value is inversely proportional to the value of Req, which decreases as Q increases.

Observing the time response for these cases in (**Figure. III. 21 Figure. III. 22, Figure. III. 23**), it can be seen how the current increases with Q and how, in case of (**Figure. III. 21**), the current is not sinusoidal. the quality factor can also be understood as a value of how good the filtering at resonant frequency is. Considering that the voltage is a square waveform at resonant frequency.

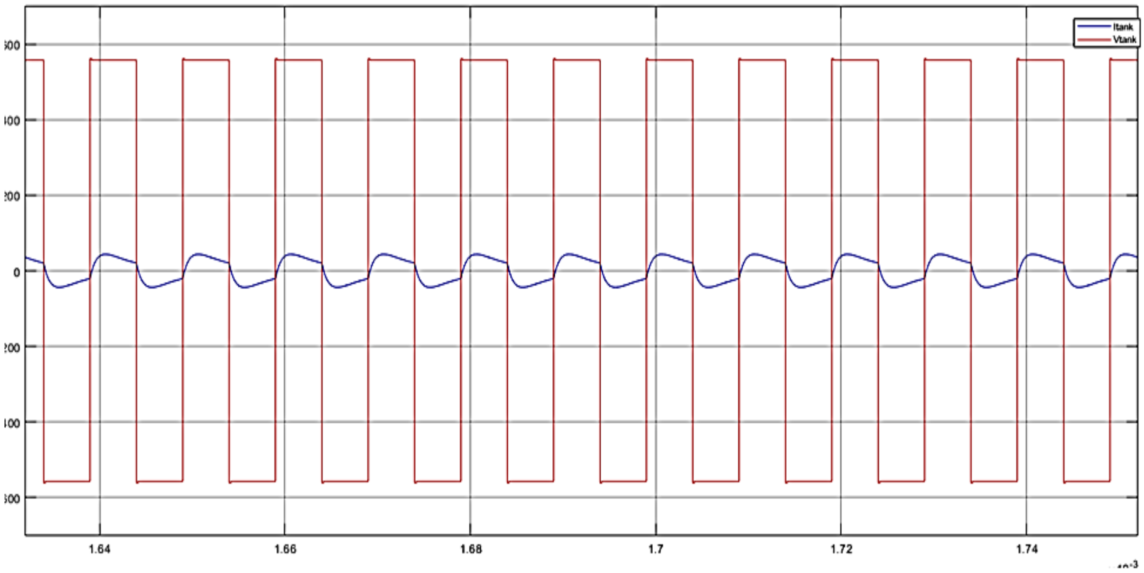

Figure. III. 21 : Voltage and current in the tank with Req = 15.58 Ω

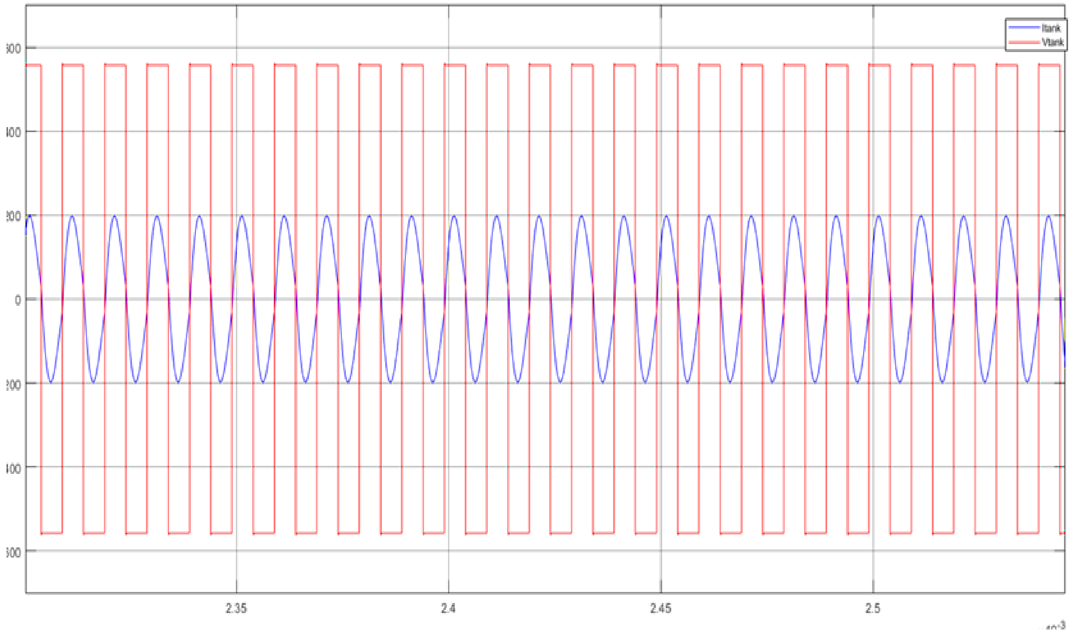

Figure. III. 22 : Voltage and current in the tank with, Req = 3.58 Ω

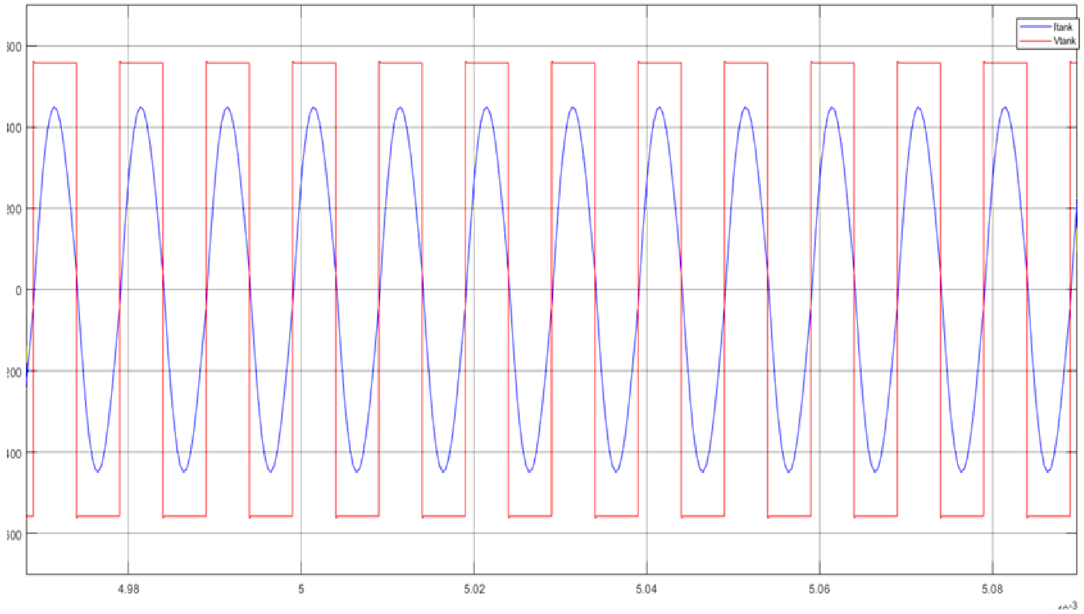

Figure. III. 23 : Voltage and current in the tank with Req = 1.58 Ω

Taking this fact into consideration, it is always interesting to have a high Q value. However, depending on the application, this is not always possible because the value of Q depends on the equivalent circuit, which is at the same time determined by the geometries and materials of the inductor-workpiece,

- **Quality factor and voltage gain**

$$\boldsymbol{U_c(\omega_r) = \frac{1}{j\omega_r C} I_{tank}(\omega_r)} \qquad \text{(Eq. III. 13)}$$

Thus, at resonant frequency, the voltage at the capacitor is Q times the voltage at the output of the inverter and 90 degrees delayed.

Similarly happens with the inductor voltage, which is equal to:

$$\boldsymbol{U_{cL}(\omega_r) = j\omega_r L I_{tank}(\omega_r) = j\omega_r L \frac{U_{tank}(\omega_r)}{R_{eq}} = jQU_{tank}(\omega_r)} \qquad \text{(Eq. III. 14)}$$

In the previous section, we discussed the significance of having high Q values in induction heating (IH) systems. However, it is important to keep in mind that as the Q value increases, the voltage at the capacitor also increases by a factor of Q. This imposes a limitation on the Q value to prevent excessively high voltages. For example, if the Q value exceeds 10, it would result in capacitors having to withstand voltages over 1000 V for an output voltage of only 100 V from the converter. This not only requires using more capacitors in series but also raises concerns about isolation and safety due to the involvement of high voltages and frequencies. While it is difficult to establish a specific limit for the Q value since it depends on the application, IH designers typically work with Q values ranging from 3 to 15.

The practical implications of this can be observed in (**Figure. III. 24,Figure. III. 25**), where voltage and current waveforms are shown for a specific tank operating at the resonant frequency. In this case, the RMS voltage across the resistance, UR_{eq}, is measured at 504 V, which coincides with the first harmonic of U_{tank} with Ue equal to 560 V. Similarly, the RMS voltage across the capacitor, UC, is approximately 1965 V, practically equal to Q times U_{tank}. Additionally, the voltage across the resistor is in phase with the tank voltage, while the voltage across the capacitor lags by 90 degrees.

When we examine the inductor voltage, U_L , we find that it leads the tank voltage (U_{tank}) by 90 degrees, although the waveform is not sinusoidal. In fact, U_L can be understood as the sum of a sinusoidal component (Q times the first harmonic of U_{tank}) and the difference between the sinusoidal voltage UR_{eq} and the square wave voltage U_{tank}. However, from a practical standpoint, (Eq. III. 14) can be used as a good approximation.

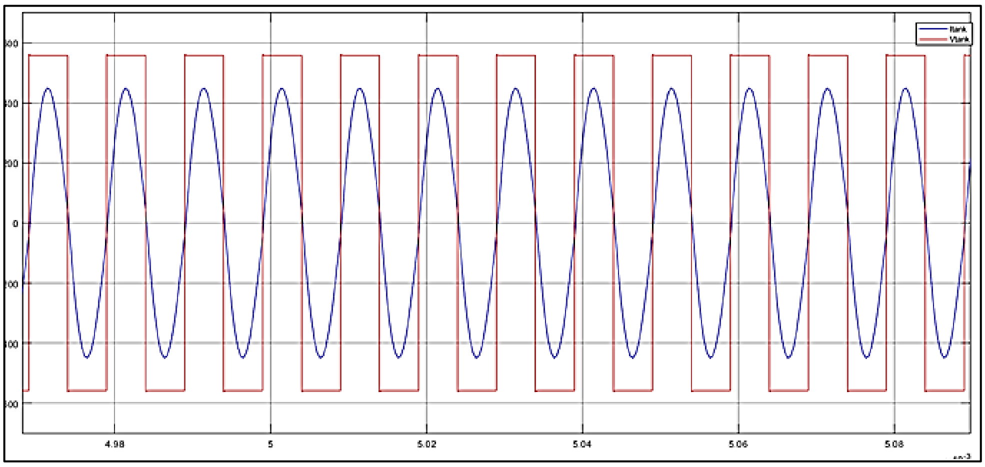

Figure. III. 24 : Voltage and current in the tank with Req = 1.58 Ω

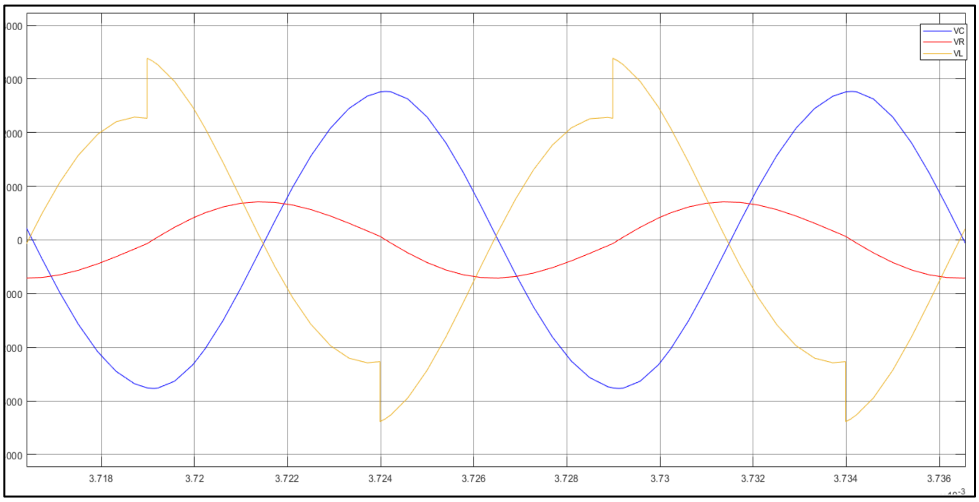

Figure. III. 25 : Voltage and current in the tank and in the RLC circuit

III.9. Power in the workpiece

With regard to the power transmitted to the workpiece, it can be easily calculated considering that Req represents the workpiece resistance. Assuming this definition, the power is equal to:

$$P = I_{tank}^{2} R_{eq} = \frac{U_{Req}^{2}}{R_{eq}} \qquad \text{(Eq. III. 15)}$$

Considering that the voltage across the resistance is equal to the first harmonic of Utank then

$$P(\omega_r) = \frac{\left(U_{R_{eq}}(\omega_r)\right)^2}{R_{eq}} = \frac{\left(\frac{4U_e}{\sqrt{2}\pi}\right)^2}{R_{eq}} = \frac{8U_e^2}{\pi^2 R_{eq}} \qquad \text{(Eq. III. 16)}$$

It is observed from (Eq. III. 16), that the power delivered to the workpiece can be controlled by the voltage of the voltage-source Ue. This is the most intuitive power control method. In this case, the model of inductor-workpiece explained has been used to introduce the manner of calculating the power. However, the analytical model can also be applied.

In that case, the inductance and resistances used for doing the calculations are the sum of them and the power delivered to the workpiece is calculated using $R\omega$.

III.10. Commutation analysis

The previous sections have discussed the concept of resonant frequency, which is the frequency at which the workpiece receives maximum power. It was explained that at this frequency, commutation occurs when the current approaches zero, resulting in reduced commutation losses. However, achieving perfect resonance in real systems is nearly impossible due to small variations in the load or inaccuracies in the control system. As a result, during normal operation, the converter operates slightly above or below the resonant frequency. This section examines these different commutation scenarios to understand the sequence of events during the commutation process and determine the preferable behavior of the converter.

(**Figure. III. 26**) illustrates a simplified diagram of a VFSRI (Variable Frequency Solid-State Resonant Inverter), highlighting the variables used in the explanations. (**Figure. III. 29 , Figure. III. 32,** and **Figure. III. 35**) depict the current and voltage on the tank. The current in SW1 and D1, along with the gate signals of the switches, are also plotted to provide a clearer understanding of the events described below the graph. It should be noted that in the case of VFSRI, to prevent short-circuits, two switches from the same inverter leg cannot be conducting simultaneously. For the purpose of this section, the dead-time is disregarded, and ideal turn-on and turn-off operations are assumed without any delays.

III.10.1. Commutating at resonant frequency ($\boldsymbol{fsw = fr}$)

Figure. III. 29 : sequence of events commutating at resonant frequency (**fsw =** fr = 100 kHz)shows the corresponding sequence for an inverter commutating at resonant frequency. In this case, the commutation, illustrated by the gate signals, occurs when the current is crossing zero. Observing SW1 and its antiparallel diode, the current is flowing through SW1half of the cycle and the diode is never conducting.

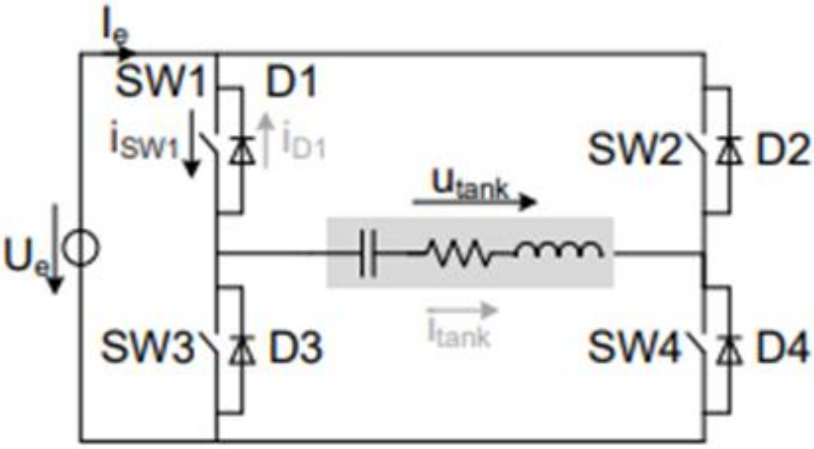

Figure. III. 26 : VFSRI circuit and variables studied

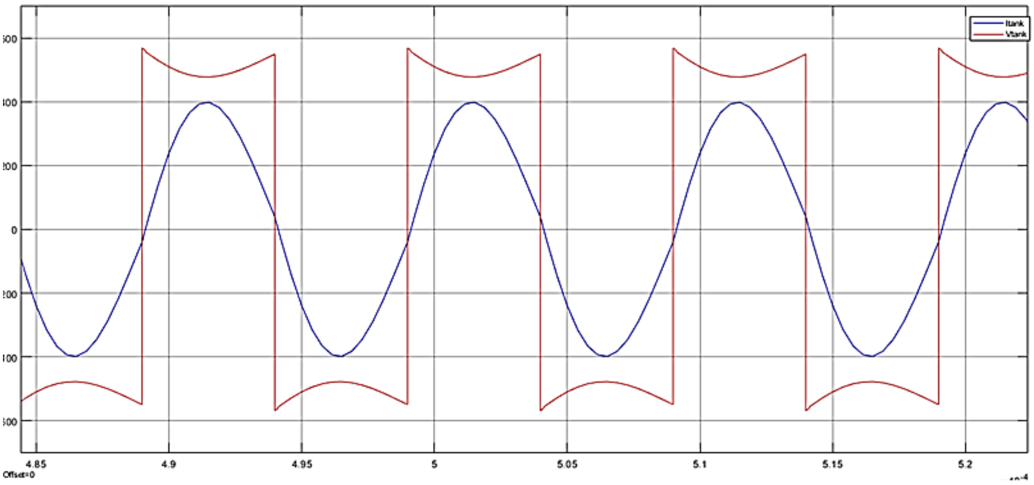

Figure. III. 27 : Output waveforms at resonant frequency ($fsw = fr =$ 100 kHz)

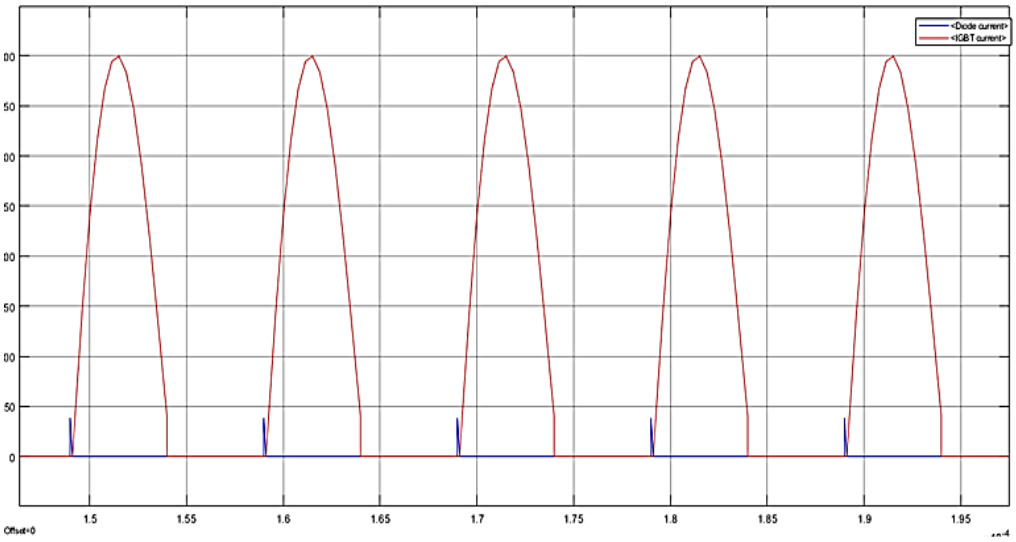

Figure. III. 28 : current in switch and diode

Sequence of events

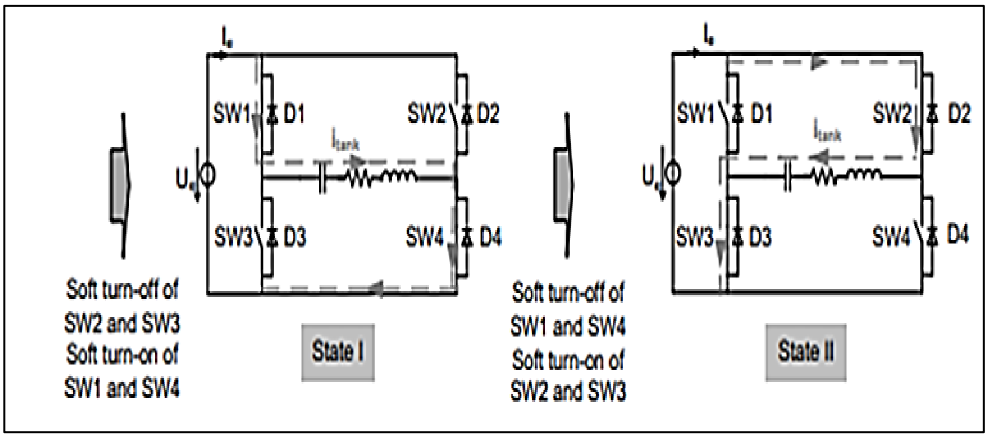

Figure. III. 29 : sequence of events commutating at resonant frequency ($fsw = fr$ = 100 kHz)

Under these circumstances there are just two possible states. The first one, when SW1 and SW4 are conducting and, the second one, when SW2 and SW3 conduct. Considering losses, there are no commutation losses because switches commutate when the current is zero. This is the ideal situation with regards to switching losses, but the probability of being at perfect resonance is low. Thus, the other situations need to be studied.

III.10.2. Capacitive switching ($fsw < fr$)

In **Figure. III. 32** , the waveforms and the corresponding sequence of events for switching below resonance are depicted. From the figure, it can be observed that the commutation and the voltage zero crossing occur after the current zero crossing. In this case, the current leads the voltage, and this type of commutation is referred to as capacitive switching. The relationship between frequency, current phase-shift, and voltage phase-shift can be seen in the Bode Diagram of (**Figure. III. 19**)

Compared to the previous case, SW1 does not conduct for half of the period, and its antiparallel diode (D2) conducts for a short period of time. Specifically, D1is forward-biased after the current zero crossing and before the turn-off of SW1. As a result, the tank current (I_{tank}) is slightly lower than in the previous case, but the difference is not significant. This difference can also be observed in the Bode diagram of (**Figure. III. 19**), where the gain decreases to a higher or lower extent depending on the Q factor and frequency.

Examining the sequence of events in (**Figure. III. 32**), in State I, the current flows through SW1 and SW4. Then, (I_{tank}) changes polarity while SW1 and SW4 are turned on, and diodes D1 and D_4 are forward-biased with zero voltage switching (ZVS) in State II. Subsequently, SW1 and SW4 are turned off with zero current switching (ZCS) because their antiparallel diodes conduct in State III. Finally, SW2 and SW3 are turned on forcefully, causing the hard turn-off of diodes D1 and D4 in State IV. States V and VI are similar to States II and III, respectively, but with the opposite switches and diodes.

In this case, the turn-off of diodes and the turn-on of switches are hard, while the turn-on of diodes and the turn-off of switches are soft. One problem that arises from the hard turn-off of diodes is the generation of large recovery currents that can create voltage spikes. This leads to increased electromagnetic interference, losses, and, in the worst-case scenario, the destruction of semiconductors. Hence, if possible, capacitive switching should be avoided.

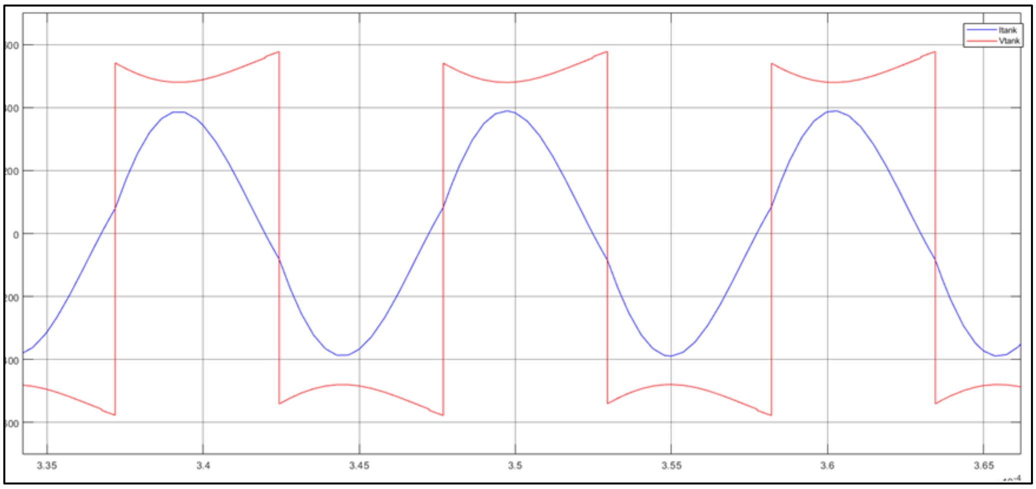

Figure. III. 30 : Output waveforms below resonant frequency ($f sw$ = 92 kHz, $f r$ = 100 kHz)

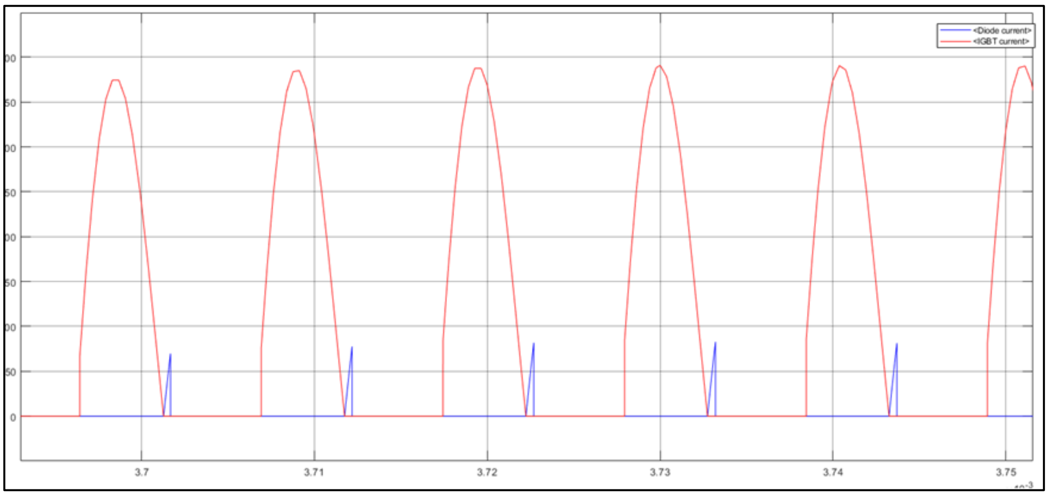

Figure. III. 31 : current in switch and diode

Sequence of events

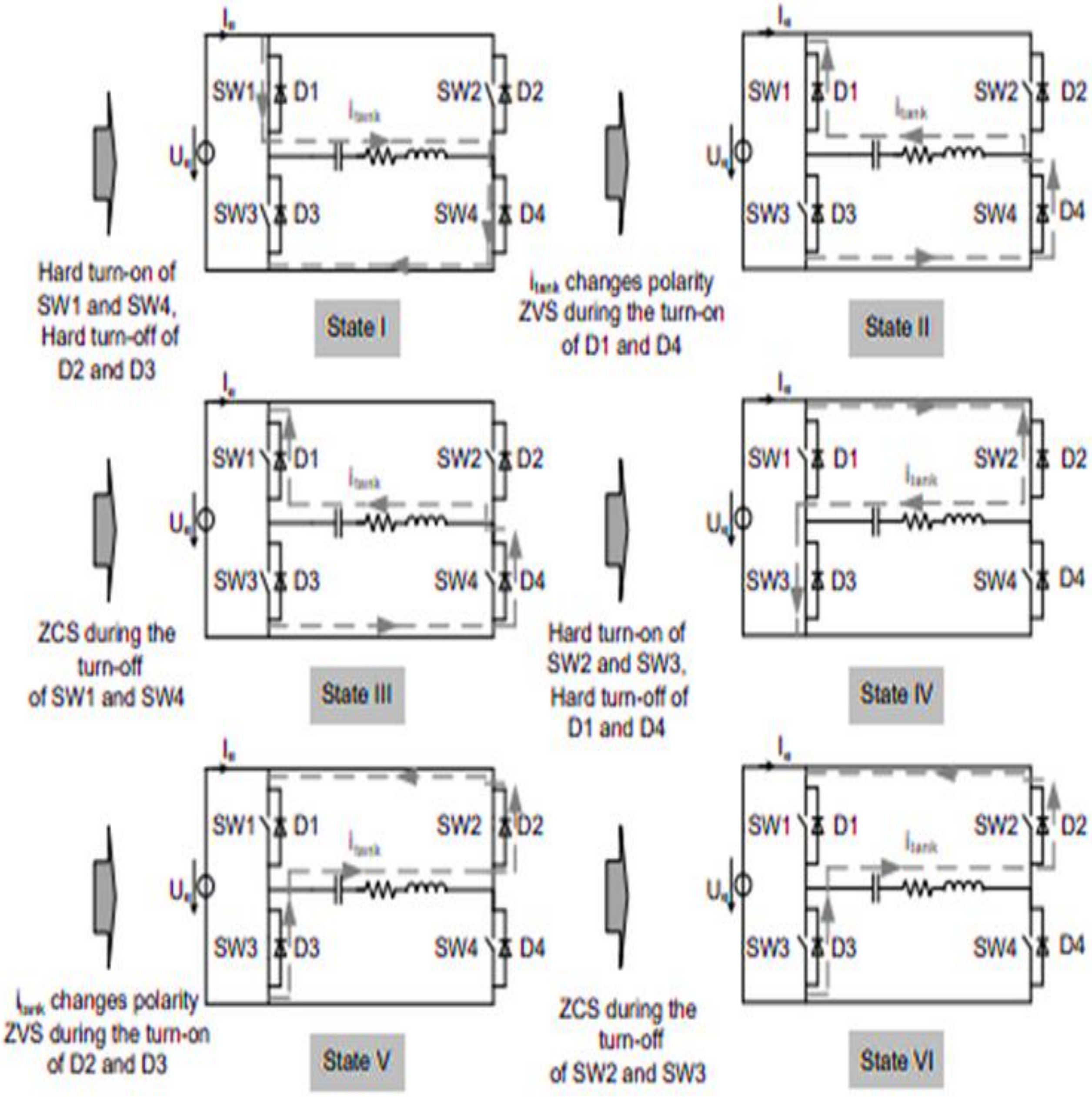

Figure. III. 32 : sequence of events commutating below resonant frequency (fsw = 92 kHz, fr = 100 kHz)

III.10.3. Inductive switching ($fsw > fr$)

When the inverter is operating above the resonant frequency, it undergoes inductive switching. This means that the current delays the voltage, and the commutation and voltage zero crossing happen before the current zero crossing. This type of switching is referred to as inductive switching.

During inductive switching, the diode D1 becomes forward-biased and conducts after the commutation and before the change in polarity of I_{tank} (the tank current). The value of $I_{tank}$is slightly lower compared to switching at resonant frequency, but the difference is not easily noticeable.

The sequence of events depicted in (**Figure. III. 35**) illustrates the different states of inductive switching. In State I, the current flows through switches SW1 and SW4. Then, SW1 and SW4 are abruptly turned off, resulting in a hard turn-on of diodes D2 and D3 (State II). Immediately after, switches SW2 and SW3 are turned on with zero voltage switching (ZVS) because the current flows through their antiparallel diodes (State III). Finally, I_{tank}changes its polarity, causing D2 and D3 to be blocked with zero current switching (ZCS) as the current starts flowing through switches SW2 and SW3 (State IV). States V and VI are similar to States II and III, but with opposite switches and diodes.

In contrast to capacitive switching, where diode turn-on and switch turn-off are hard, in inductive switching, diode turn-off and switch turn-on are hard. However, the turn-off of diodes and turn-on of switches are soft. Due to the challenges associated with hard turn-off of antiparallel diodes and the low likelihood of achieving perfect resonance, it is recommended to operate the inverter above the resonant frequency. In such cases, switches with unidirectional voltage capability and bidirectional current capability must be used, which necessitates the inclusion of antiparallel diodes.

III.10.4. Additional considerations

Up until now, the analysis has assumed an ideal circuit with ideal sources, disregarding the impact of dead-time and parasitic components. The switches have been assumed to be ideal, and no information has been provided regarding the current in the converter. However, it is essential to take these parameters into account during the design process as they significantly influence the converter's performance.

in this section, we will explore the influence of parasitic capacitors and dead-time on commutation and switching frequency. Additionally, we will discuss important considerations related to power semiconductors in VFSRI (Voltage-Fed Series Resonant Inverter) applications.

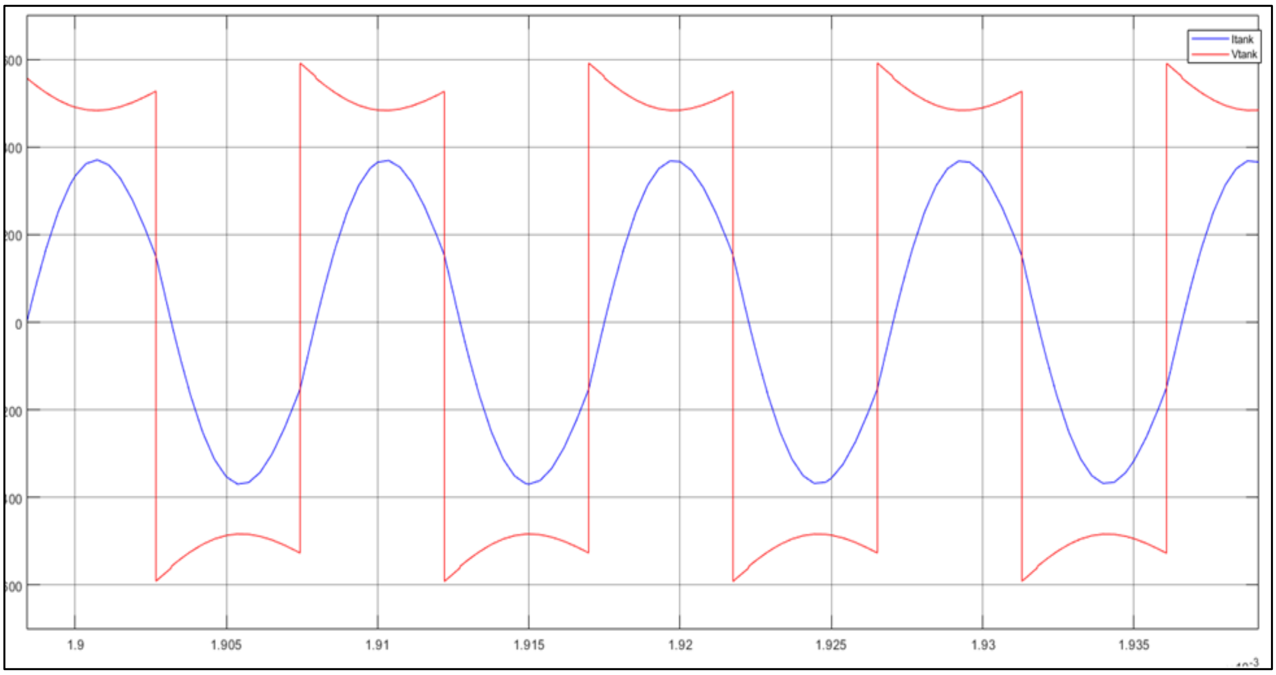

Figure. III. 33 : Output waveforms above resonant frequency (fsw = 108 kHz, fr = 100 kHz)

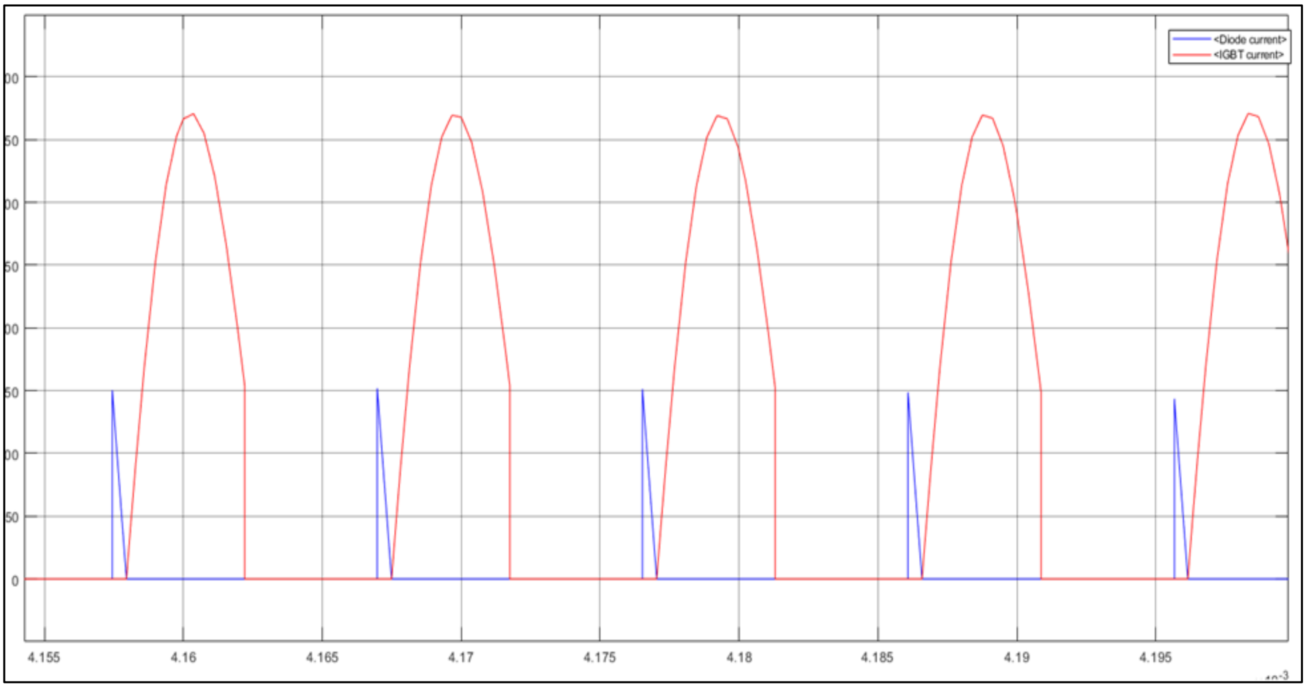

Figure. III. 34 : current in switch and diode

Sequence of events

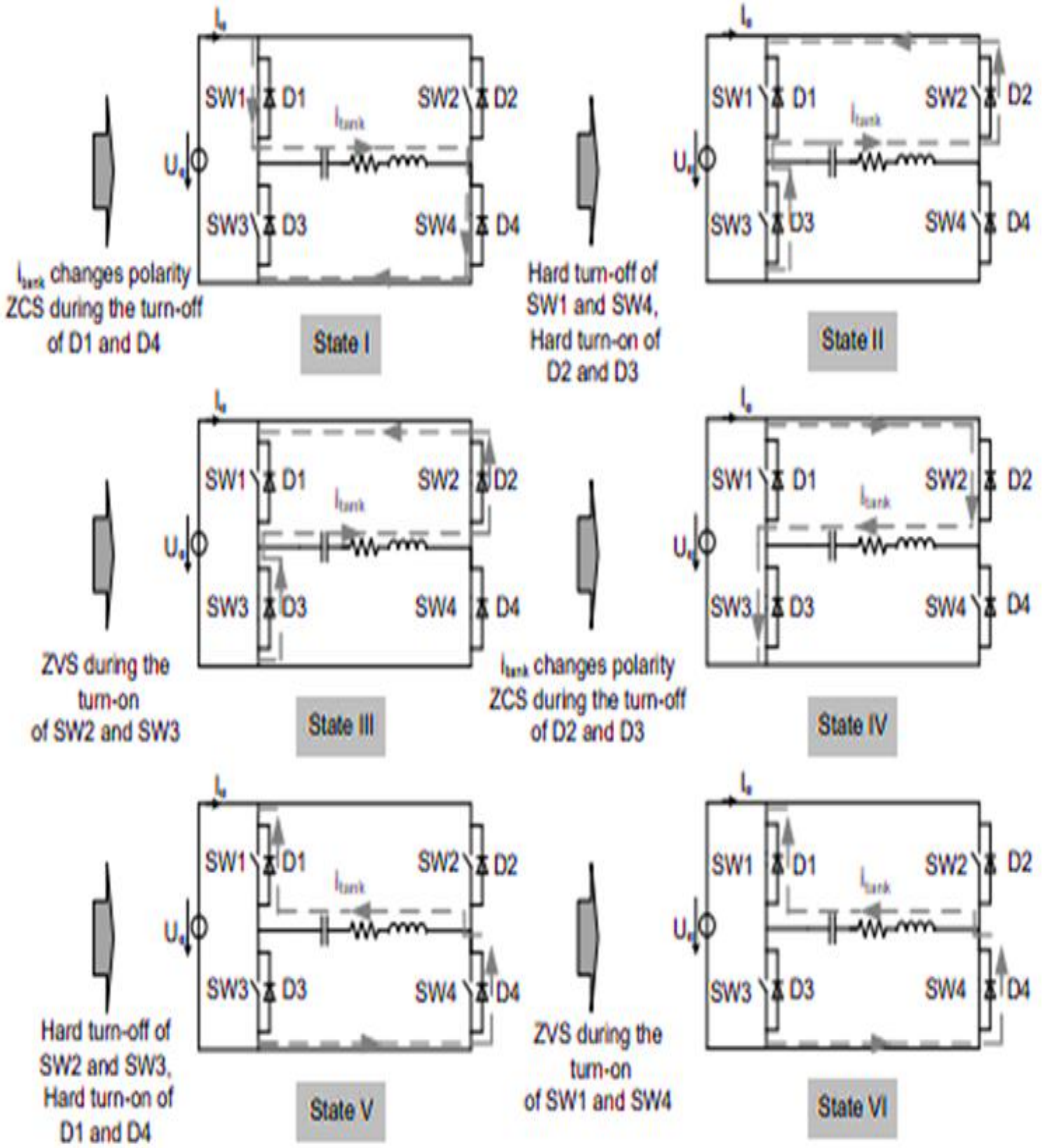

Figure. III. 35 : sequence of events commutating above resonant frequency (fsw = 108 kHz, ƒr = 100 kHz)

Finally, the need of a transformer between the load and the converter due to the high currents through semiconductors is exposed

III.11. Commutation sequence considering parasitic capacitances and dead-time

Due to issues arising from reverse recovery currents in diodes, many authors perform switching above the resonant frequency. However, these analyses often overlook the consideration of parasitic capacitances in semiconductors and the dead-times between switches. This section aims to explain the influence of these parameters.

Depicts the electrical scheme of a VFSRI, taking into account parasitic capacitances (Cp). It is worth noting that Cp includes both the parasitic capacitance and, if present, the snubber. Assuming the inverter switches above resonance, (**Figure. III. 37**) showcases the output waveform and events, accounting for these capacitances and the dead-time between switches. The states illustrated in this figure are connected to those defined in (**Figure. III. 35**).

Upon observing (**Figure. III. 35**), the sequence for achieving soft-switching during inductive switching is presented. The chronological order of events in this figure unfolds as follows:

- Switches SW2 and SW3 experience challenging turn-off.
- The parasitic capacitance Cp of SW2 and SW3 charges, while Cp of switches SW1 and SW4 discharges. This charging process raises the voltage of U_{tank}until it reaches U_e.
- When U_{tank}surpasses U_e, the antiparallel diodes D1 and D4 become forward-biased.
- Switches SW1 and SW4 are turned on with zero-voltage switching (ZVS) as their antiparallel diodes conduct.
- The current i_{tank}undergoes a polarity change, flowing through SW1 and SW4, and turns off the antiparallel diodes D1 and D4 with zero-current switching (ZCS).

It was previously assumed that ZVS occurs during switches' turn-on and ZCS during diodes' turn-off in cases of switching above resonance. However, (**Figure. III. 37**) reveals that ZVS and ZCS do not consistently occur.

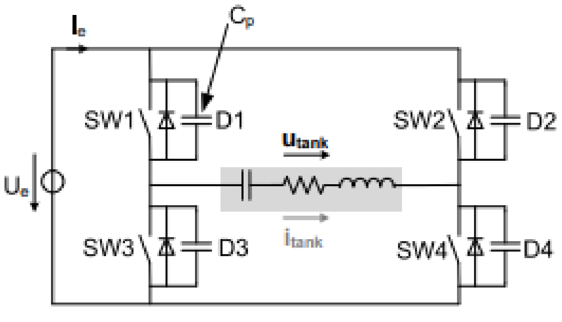

Figure. III. 36 : VFSRI considering parasitic capacitances Cp.

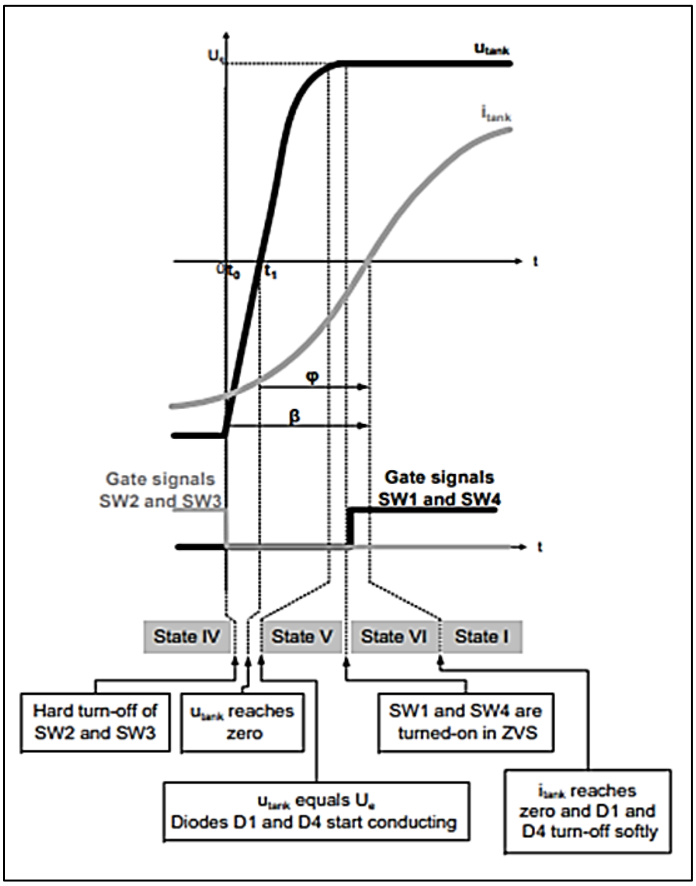

Figure. III. 37 : *Output waveforms and sequence to have ZVS and ZCS commutating above resonance*

For instance, in the case of short dead-times, SW1 and SW4 are switched on before U_{tank} reaches U_e, resulting in the absence of Zero Voltage Switching (ZVS). This situation can occur when the capacitance Cp is high and takes longer than the available charging time. Another scenario is when there is a low phase-shift between voltage and current, and the current changes polarity before SW1 and SW4 are turned on. In this case, neither ZVS nor Zero Current Switching (ZCS) occurs. [25]

$$\boldsymbol{\beta \geq arccos\left[1 - \frac{2U_e C_p \omega}{\hat{\imath}_{tank}}\right]} \qquad \text{(Eq. III. 17)}$$

And

$$\boldsymbol{\varphi \geq arccos\left[1 - \frac{U_e C_p \omega}{\hat{\imath}_{tank}}\right]} \qquad \text{(Eq. III. 18)}$$

where (**see Figure. III. 37**)

- β, is the phase-shift between the instant at which the gate signal of the switch becomes low and the moment at which i_{tank} changes polarity.
- φ is the phase-shift between U_{tank} and i_{tank}.

- $\hat{\imath}_{tank}$ is the amplitude of i_{tank}.
- $U_e$is the voltage of the DC source.
- $C_p$is the sum of the parasitic capacitance and the snubbers of the switches.

Upon observing (Eq. III. 17) and (Eq. III. 18), it becomes evident that achieving proper commutation requires complex control. Furthermore, in cases of low currents or high capacitances, the values of β and ϕ are high. Under such circumstances, the switching frequency and the reactive power supplied by the inverter increase. To maintain the same active power output, a higher voltage U_e is required.

III.12. Conclusion

In this chapter, we explored different types of converters and tank configurations used in induction heating applications, specifically for continuous wire heating.

The two most common converter topologies in induction heating are VFSRI (Voltage-Fed Series Resonant Inverter). In VFSRI, the heating inductor is connected in series with a capacitor, and the inverter is powered by a constant voltage source. where the current and voltage are in phase and commutation losses are minimized.

Ideally, the inverters should operate at the resonant frequency. However, due to diode reverse-recovery effects or parasitic components, the actual commutation frequency may be higher. This allows for avoiding issues such as diode reverse-recovery in VFSRI and overvoltage’s in CFPRI. Each topology has its own advantages and disadvantages, these differences make them suitable for different applications, leading to their coexistence in the field of induction heating.

General Conclusion

In conclusion, induction heating has emerged as a versatile and efficient method for heating and melting materials in various industrial applications. Its advantages, such as high energy efficiency, rapid heating, precise temperature control, and cleanliness, make it a preferred choice for processes such as metal melting, surface hardening, heat treatment, and induction brazing.

Throughout this research, we have explored the generalities of preheating, the basics of induction heating, and the components involved in induction heating systems. We have discussed the different types of energy sources used in smelting and heating furnaces, including solid fuel, liquid and gas fuel, as well as electric furnaces. Induction heating, with its induction furnaces and various types of inductors, has been thoroughly examined, highlighting its advantages and distinctive characteristics.

Furthermore, we have discussed the principles of induction heating, including the induction heating/melting process and the electrical model of the inductor-workpiece system. The analysis of energy losses due to the Joule effect and hysteresis has provided insights into the efficiency of induction heating. Estimating the inductor and power supply requirements, along with examining thermal and electrical efficiencies, has provided valuable insights for designing and optimizing induction heating systems.

Moreover, the discussion on induction heating converters, focusing on power semiconductors, chopper modeling, and voltage-fed series resonant inverters, has provided an understanding of the electrical aspects of induction heating systems. The analysis of resonant frequency, quality factor, power transfer to the workpiece, and commutation analysis has contributed to a comprehensive overview of converter operation.

Overall, this research has provided a comprehensive understanding of induction heating, encompassing its principles, components, and technical considerations. It serves as a valuable resource for researchers, engineers, and industry professionals seeking to harness the benefits of induction heating in their respective fields. With its high efficiency and versatility, induction heating continues to be at the forefront of modern heating and melting processes, driving advancements and innovations in various industries.

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Annexe

المطلب الأول

عرض القطاع السوقي

يعتمد عرض القطاع السوقي على نوع آلة التسخين بالحث المحددة والصناعة التي تستهدفها. ومع ذلك، يمكن تقسيم القطاع السوقي لآلات التسخين بالحث إلى عدة فئات عامة:

الصناعة والتصنيع:

- تشمل هذه الفئة الصناعات التي تحتاج إلى التسخين بالحث لعمليات التصنيع والتشكيل والإنتاج، مثل صناعة المعدن والبلاستيك والزجاج والمطاط والورق

السيارات والنقل:

- تشمل هذه الفئة تطبيقات التسخين بالحث في صناعة السيارات والنقل، مثل التسخين الموجه لتجميع الأجزاء أو عمليات التلحيم بالحث.

الإلكترونيات والكمبيوتر:

- تشمل هذه الفئة تطبيقات التسخين بالحث في صناعة الإلكترونيات والكمبيوتر، مثل تصنيع الدوائر الإلكترونية ولحام الأجزاء الصغيرة.

الطب والعلوم الحيوية:

- تشمل هذه الفئة تطبيقات التسخين بالحث في صناعة الطب والعلوم الحيوية، مثل التسخين الموجه لعمليات التحليل الكيميائي أو تصنيع الأدوية.

الأغذية والمشروبات:

- تشمل هذه الفئة تطبيقات التسخين بالحث في صناعة الأغذية والمشروبات، مثل التسخين السريع لتجهيز الطعام أو تسخين المشروبات

السوق المستهدف:

القطاع الصناعي: يشمل هذا القطاع المصانع والمرافق الصناعية المختلفة. قد تحتاج الشركات الصناعية إلى أنظمة تسخين بالحث لتسخين وتشغيل المعدات والعمليات الصناعية مثل:

- صناعة الصلب والمعادن
- صناعة النفط والغاز
- صناعة الكيماويات
- شركات التصنيع
- ورش تصليح السيارات

ومن الأسباب التي اخذناها بعين الاعتبار والتي ركزنا عليها في اختيار هذا السوق منها:

1. حجم السوق
2. الربحية
3. احتياجات محلية قائمة
4. قدرة المنافسة المحدودة
5. الدعم الحكومي:
6. الخبرة والموارد
7. الطلب
8. التوجه نحو الاستدامة والكفاءة الطاقية

المنافسين في السوق

اهم المنافسين المباشرين في السوق الجزائرية المستوردون

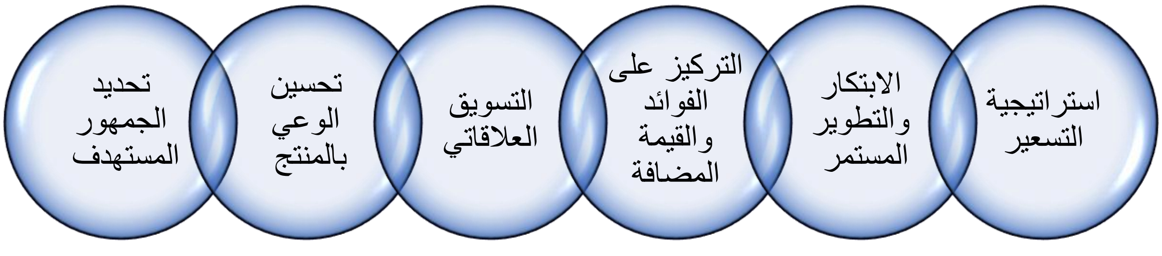
نقاط الضعف

ومع ذلك، في العموم، يمكن تحديد بعض النقاط التي قد تكون ضعف توفير آلات التسخين بالحث. هذه النقاط قد تتضمن

إستراتيجية التسويق

نهتم في مؤسستنا برضا العملاء ونعتبرهم رأس المال الحقيقي للشركة. لذا، نقدم لهم قنوات اتصال مباشرة وفعالة لتقديم شكاويهم واقتراحاتهم.

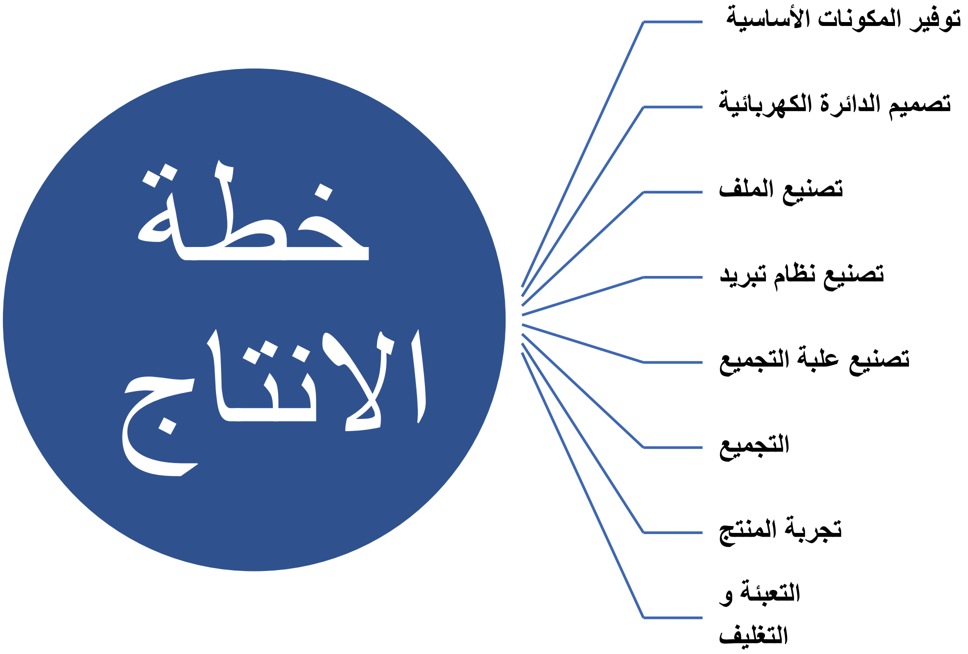
بالإضافة إلى ذلك، نتبنى استراتيجية تسويقية بأسعار تنافسية حيث نهدف إلى تقديم منتجات ذات جودة عالية بأسعار مناسبة ومنافسة في السوق. نحقق ذلك من خلال تحكمنا في:



المطلب الثاني

خطة الانتاج والتصنيع للآلة

خطة الإنتاج والتصنيع للآلة التسخين بالحث تشمل عدة عناصر رئيسية. فيما يلي نموذج عام لخطة الإنتاج والتصنيع



التموين:

- **إدارة المخزون:** الحفاظ على نظام فعال لإدارة المخزون لضمان مستويات المخزون الكافية مع تقليل المخزون الزائد أو المتقادم.
- **تحليل الموارد المطلوبة:** قم بتحديد الموارد المختلفة التي تحتاجها لتنفيذ المشروع، مثل المواد الخام، والمعدات، والتقنيات، والعمالة، والمساحة الفعلية، والتمويل، والوقت. تحليل الاحتياجات بدقة سيساعدك في التخطيط الجيد وتحقيق النجاح.
- **التعاون مع الموردين:** بناء علاقات قوية واستراتيجية مع الموردين الموثوقين والذين يمكنهم توفير الموارد اللازمة لمشروعك. قم بتقييم واختيار الموردين الذين يقدمون جودة عالية وأسعار مناسبة وخدمة موثوقة
- **التخطيط الجيد للإمدادات:** قم بوضع خطة إمدادات مفصلة ودقيقة للموارد المختلفة المطلوبة للمشروع. حدد الوقت المناسب لطلب المواد وتسليمها لضمان استمرارية العمل وتجنب أي انقطاعات غير مرغوب فيها .
- **إدارة المخاطر:** قم بتحليل المخاطر المحتملة التي يمكن أن تؤثر على تموين المشروع ووضع استراتيجيات للتعامل معها. قد تشمل هذه المخاطر تأخر التسليم، نقص الموارد، تغيرات في السوق، أو مشاكل في الجودة. قم بتحضير خطة احتياطية للتعامل مع أي مشكلة غير متوقعة .
- **متابعة وتقييم الأداء:** قم بمراقبة وتقييم أداء تموين المشروع بانتظام. قيم مد ى الامتثال للجدول الزمني وجودة الموارد وكفاءة التكلفة. قم بإجراء التحسينات اللازمة والتعديلات في حالة وجود أي تحسينات مطلوبة.

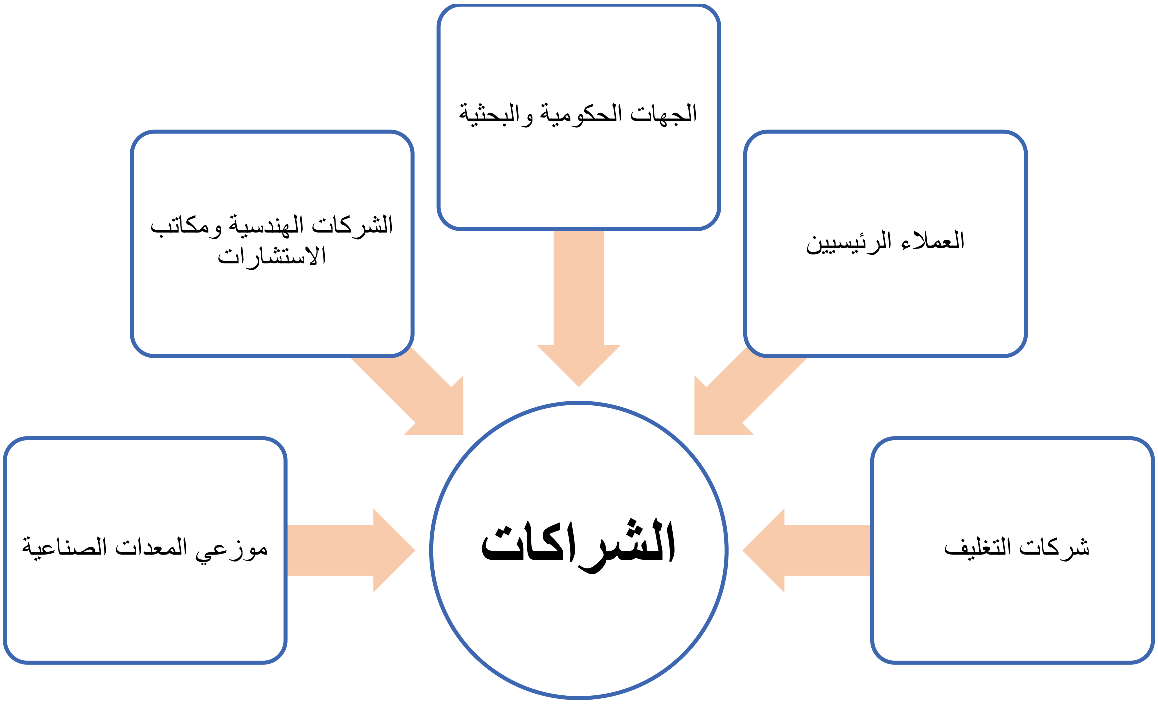
اليد العاملة:

في حالة شركتنا المختصة في صناعة التسخين بالحث، عدد العمال عادةً يكون محدودًا. ويعتمد عدد العمال على عدة عوامل مثل نطاق الإنتاج وحجم الشركة والعمليات المطلوبة.

قد يكون عددهم في النطاق من 15 إلى 20 عاملًا، وهذا يعتمد بشكل كبير على حجم الإنتاج والاحتياجات العملية

- **فريق الإدارة والتخطيط**: يشمل الإدارة العامة وإدارة المشروع والتخطيط والمراقبة المالية والإدارة الإستراتيجية والتسويق (3 أعضاء)
- **فريق الهندسة والتصميم**: يعمل على تصميم وتطوير الآلات والمكونات وتحسين العمليات والابتكار التقني(2 عمال)
- **فريق الإنتاج والتصنيع**: يشمل عمال الإنتاج والفنيين والمشرفين الذين يقومون بتشغيل وصيانة وإصلاح الآلات والمعدات (5 عمال)
- **فريق ضمان الجودة**: يعمل على ضمان جودة المنتج والتحقق من التوافق مع المعايير ومتطلبات العملاء(2 عمال)
- **فريق البحث والتطوير**: يعمل على تطوير تقنيات وعمليات جديدة وتحسين الأداء وتقديم المزيد من الابتكارات (فريق الإدارة)
- **فريق الوقاية والأمن الصناعي**: إجلاء العمال في حالة الخطر وحماية الممتلكات (2 عمال)
- **عمال عاديين**: سائقين ، عمال مساعدين، عمال نظافة.(5 عمال)

الشراكات الرئيسية



المطلب الثالث

التحليل المالي للمشروع

ان التمويل يعتبر مصدر حساسا في مشروع ما باعتباره القلب النابض الذي يعطي حياة له.

يعتبر ركيزة المشروع لاستثمار وتحقيق التنمية الاقتصادية ويعطي للمشروع مزاولة نشاطه حتى يبلغ القدرة الانتاجية له من جهة اخرى توفير مناصب شغل لخفض نسبة البطالة.

ان التمويل الكافي للمشروع يعطيه ديمومة وتطوير الاستراتيجية مستقبلا.

الدراسة التقنية للمشروع:

المقر:

المصنع	برج بوعريريج	كراء	300م^{2}	20000دج

تهيئة المحل:

الفضاء	وصف	الموردين	التكلفة
المصنع	شبكة الانترنت ADSL 4méga	اتصالات الجزائر	2000
المصنع	مادة طلاء لدهن المحطة	محل لبيع طلاء	10000
المصنع	كهرباء + ماء	سونلغاز + ADE	5000

تجهيز المحل:

المعدات	الكمية	سعر الوحدة	المبلغ
كرسي نوع 01	01	5000 دج	5000دج
كراسي نوع 02	04	2500 دج	10000دج
حاسوب محمول	01	70000دج	70000دج
لوحة المحل	01	26000 دج	26000دج
عارضة المحل	01	20000دج	20000دج
خزانة	05	10000دج	50000دج
مكتب	01	20000دج	20000دج
كاميرات مراقبة	03	10000دج	30000دج
المجموع	/	/	231000دج

موظفي المؤسسة:

العاملين	الوظيفة	العدد	الراتب الشهري
مدير المؤسسة وشريكه	التسيير، المحاسبة	03	100000 دج
تقنيين	الصيانة والمراقبة	02	60000دج
عمال المصنع	التجميع والتعبئة	10	30000دج

المعدات:

المعدات	الكمية	السعر الوحدة	المبلغ
آلات القطع	07	4500دج	31500دج
آلات التشكيل	06	5500دج	33000دج
معدات اللحام والقطع	04	8000دج	32000دج
معدات الرفع والتحميل	03	7000دج	21000دج
معدات القياس والاختبار	10	2000دج	20000دج
معدات النقل والتخزين	03	3000دج	9000دج
معدات الصيانة والإصلاح	05	4000دج	20000دج
معدات السلامة والحماية (لباس، قفازات)	15	5000دج	75000دج
معدات التحكم والتشغيل	10	6000دج	6000دج
المعدات الداعمة والبنية التحتية	22	1500دج	33000دج
المجموع	85	46500	280500دج

دراسة التكلفة الكلية للمشروع:

التكلفة الكلية للمشروع		
التمويل	المبالغ	المجموع
مساهمة الشريكين % 8	500000دج	2700000دج+ اضافة مالية ب 50000دج
القرض بدون فوائد % 22	700000دج	
البنك % 70	15000000دج	

نموذج العمل التجاري:

شرائح العملاء

شركات صناعة العتاد الطبي
صناعة السيارات
كوندور، جيون، كريستور للكهرومنزلية
الحرفيين (صائغ، سباك، لحام)

العلاقات مع العملاء

عروض وتخفيضات
برامج الولاء
تقديم ضمانات
خدمة ما بعد البيع (الصيانة وحل المشاكل)
نقاط البيع
بطاقات العمل

القنوات

وسائل الإعلام التقليدية
التسويق الرقمي
التسويق التابع
المبيعات المباشرة
موقع إلكتروني خاص بالمؤسسة

القيم المقترحة

نظام التسخين بالحث هو نظام يستخدم لتسخين المواد باستخدام تقنية التسخين بالحث الكهرومغناطيسي يستخدم هذا النظام في مجموعة واسعة من الصناعات والتطبيقات حيث يكون التسخين السريع والدقيق ضروريًا. يوفر هذا النظام كفاءة عالية وتحكم دقيق في درجة الحرارة، مما يساهم في زيادة الإنتاجية وتحسين جودة المنتجات
تقليل التكاليف التشغيلية
توفير الأمن والسلامة

الأنشطة الرئيسية

التسويق
التصنيع والجودة
البحث والتطوير
شراء المواد الأولية

الموارد الرئيسية

موارد مالية
موارد بشرية (أصحاب المشروع، فريق متخصص في التطوير والتصميم، يد عاملة مؤهلة)
موارد مادية (المعدات، المقر)

الشراكات الرئيسية

الموزعين والوكلاء
موردي المواد الخام

مصادر الإرادات

بيع مباشر
صيانة وخدمات ما بعد البيع

هيكل التكاليف

تكاليف متغيرة:
تكلفة الكهرباء
تكاليف الصيانة المستهلكة
تكاليف الإنتاجية
تكاليف التسويق والتوزيع

تكاليف ثابتة:
تكلفة الاستثمار الأولية
تكاليف الصيانة الدورية
تكاليف الإيجار والتأمين
تكاليف التدريب والتعليم
أجور العمال

تقدير المبيعات السنوية:

الشهر	المنتج	عدد اسابيع	قيمة مبيعات شهرية
01	2	04	50000000دج
02	3	04	7500000دج
03	3	04	7500000دج
04	4	04	100000000دج
05	5	04	125000000دج
06	6	04	150000000دج
07	7	04	175000000دج
08	4	04	100000000دج
09	5	04	125000000دج
10	8	04	200000000دج
11	10	04	250000000دج
12	7	04	175000000دج
قيمة السنوية الاجمالية	/	/	/

التوصيات

تعتبر عملية تصنيع وتوزيع جهاز التسخين بالحث عملية معقدة تشمل عدة عناصر مثل الإمداد بالمواد الخام والتصنيع والتسليم. وقد واجهتنا تحديات أخرت في عمليات الإنتاج بسبب عوامل خارجة عن السيطرة، وهذا مما أثر على شركتنا بعدم توفر حسابات دقيقة في حجم المبيعات السنوية والعائدات المالية، لأن الأمر متروك لكمية العرض والطلب على المنتج في السوق

كل ما تطرقنا اليه في المطلب الأخير (التحليل المالي) يحتمل الزيادة او النقصان وذلك راجع لحجم الشركة وقدرتها على الإنتاج